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DISTRIBUTED BEAMFORMING IN A SWARM UAV NETWORK

by

İbrahim KOCAMAN

March 2008

Thesis Advisor:	David Jenn
Second Reader:	Terry Smith

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The use of wireless communication techniques and network centric topologies with unmanned aerial vehicles (UAV) within modern warfare concepts makes it possible to utilize new distributed beamforming applications. The objective of this research is to combine the concept of wireless beamforming in opportunistic random arrays with the concept of swarm UAVs. A considerable amount of research has already been done about the feasibility and advantages of opportunistic arrays for a single platform. Distributed beamforming techniques are widely applied by many researchers. The use of swarm UAV concepts for a widely dispersed wirelessly networked opportunistic array may anticipate many advantages over single platform-borne opportunistic arrays. Major challenges are synchronization and localization, which are caused by the mobile structure of the proposed network topology. Possible solutions to these problems are proposed.

In this thesis the use of swarm UAVs for jamming is analyzed. Closed form expressions for jamming power versus the number of UAVs, ranges, degree of transmitter coherence, and quality of beamforming are derived. It was found that even for low quality beamforming (large phase errors, or poor synchronization) significant improvements in system performance is still achievable.

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DISTRIBUTED BEAMFORMING IN A SWARM UAV NETWORK

İbrahim KOCAMAN
1st Lieutenant, Turkish Air Force
B.S., Turkish Air Force Academy, 2002

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March 2008

Author: İbrahim KOCAMAN

Approved by: David Jenn
Thesis Advisor

Terry Smith
Second Reader

Dan Boger
Chairman, Department of Information Sciences

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I. INTRODUCTION

A. GENERAL

Military systems around the world have been using Unmanned Aerial Vehicles (UAVs) within their war fighting concepts for decades. The use of UAVs on the battlefield has gradually increased by means of quantity and diversity of the applications. Recent and ongoing improvements in communications and electronics introduced new concepts and applications that have increased the use and importance of UAVs on the battlefield.

Wireless networking and distributed beamforming are two possible applications that can further increase the use of UAVs for electronic warfare (EW) applications.

B. MOTIVATION

Today, the battlefield is electronically more complex than it used to be. The use and exploitation of the electromagnetic (EM) spectrum has become crucial for military units. This extensive use of the EM spectrum made electronic warfare a key parameter to mission success. Besides changing military tactics, the concept of EW itself has also evolved. EW missions fall into following subdivisions:

(i) Electronic Attack (EA)

(ii) Electronic Protection (EP)

(iii) Electronic Support (ES) or Electronic Warfare Support

Reference [1] defines EW and its subdivisions as follows:

Electronic Warfare: Any military action involving the use of electromagnetic and directed energy to control the electromagnetic spectrum or to attack the enemy. Electronic warfare is one of the five core capabilities of information operations. The three major subdivisions within electronic warfare are electronic attack, electronic protection, and electronic warfare support.

Electronic Attack (EA): The division of electronic warfare involving the use of electromagnetic energy, directed energy, or anti-radiation weapons to attack personnel, facilities, or equipment with the intent of degrading, neutralizing, or destroying enemy combat capability. Electronic attack is considered a form of fires.

Electronic Protection (EP): The division of electronic warfare involving passive and active means taken to protect personnel, facilities, and equipment from any effects of friendly or enemy employment of electronic warfare that degrade, neutralize, or destroy friendly combat capability [30].

Electronic Warfare Support (ES): The division of electronic warfare involving actions tasked by, or under direct control of, an operational commander to search for, intercept, identify, and locate or localize sources of intentional and unintentional radiated electromagnetic energy for the purpose of immediate threat recognition, targeting, planning, and conduct of future operations. Thus, electronic warfare support provides information required for decisions involving electronic warfare operations and other tactical actions such as threat avoidance, targeting, and homing.

In order to overcome known and emerging threats over the battlefield, military doctrines utilize EA more than in the past. In most cases, a large jammer platform (usually an aircraft assigned as a jammer) provides the necessary EA capability. Another option is to use unmanned aerial vehicles (UAVs) in EA missions.

Both of these choices have their own trade-offs. While large platforms are able to carry much higher jamming power than the relatively small UAVs, their large structure leaves a much bigger radar signature than that of UAVs. Another great challenge to be addressed over the battlefield is the threat. The threat over the battlefield includes all types of adversary defensive units and activities. The availability of the technological advancements in the missile industry has also made asymmetric threats very capable against conventional military tactics. The major advantage of UAVs over larger single platforms is that, due to their small sizes, UAVs are less vulnerable to threats and thus require less self-defense precautions.

A single UAV platform is obviously not capable of carrying an EA jammer kit that matches the range capability and jammer power of a larger jammer aircraft. But similar to the extension from a single antenna to an antenna array, a swarm of UAVs acting collectively can match the parameters of a manned jammer platform. In order to achieve the anticipated gain and range enhancements, the concepts of opportunistic arrays and wireless beamforming can be utilized for a swarm of UAVs.

An opportunistic array is a distributed array where the elements are placed at available open locations, rather than in a rigid periodic arrangement. Figure 1 and 2 shows some examples of opportunistic arrays.

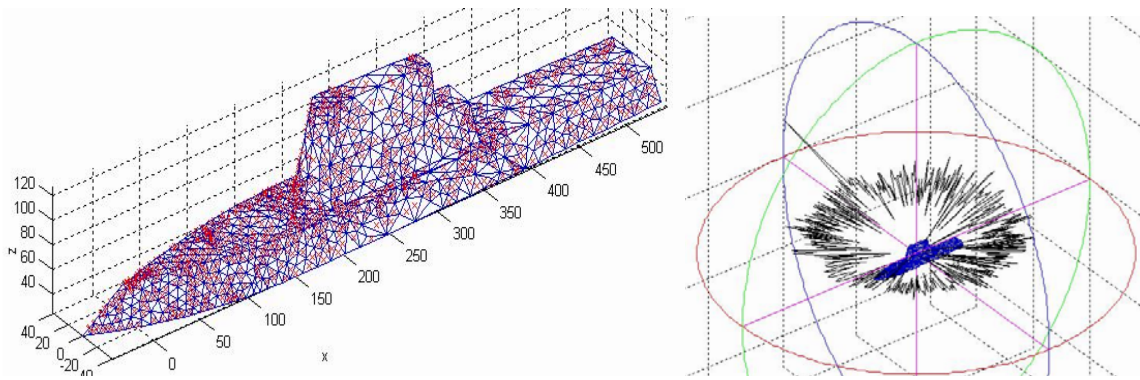

Figure 1. Example of an array of sensors or antennas distributed over a ship (left) and a coherent radiation pattern (right) (From [9]).

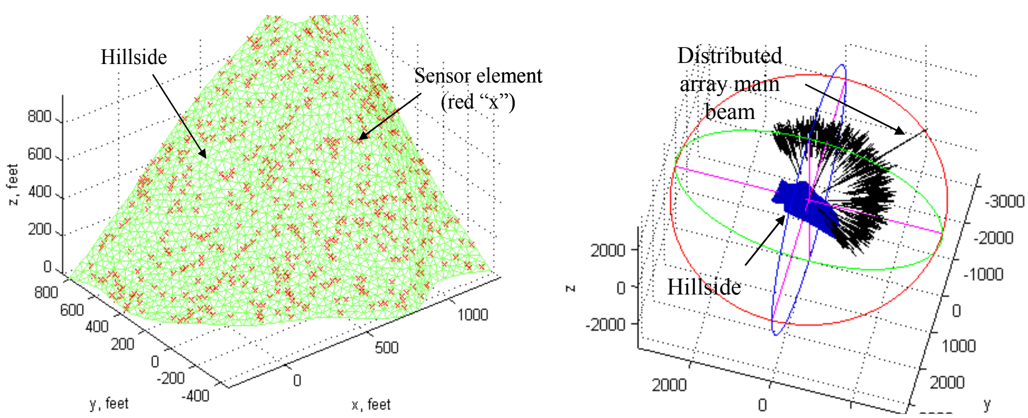

Figure 2. Example of an array of sensors or antennas distributed over a hillside (left) and a coherent radiation pattern (right) (From [9]).

Wireless beamforming has also been an area of interest over the last several decades. Beamforming is a signal processing technique that is used to increase efficiency in sensor networks. In conventional phased arrays, a beamformer circuitry is used to achieve the desired radiation characteristics such as beam direction, sidelobe level and gain. When the beamformer circuitry is replaced with a wireless network, the technique is often referred as wireless beamforming or distributed beamforming [2, 3].

Applying wireless beamforming in a swarm UAV network has its own challenges due to the highly mobile structure of the network elements. Similar to the shipboard radar opportunistic array in Figure 1, the network elements are self-standing digital transmit/receive (T/R) modules with no hardwire connections. The specific architecture of the modules depends on the EW function. Transmit channels are required for communications, radar and jamming; receive channels for radar, communications, and electronic intercept. Furthermore, every single UAV is powered on its own and the digital transmit/receive (T/R) module onboard every single UAV is fed by its own local oscillator. Thus, sensor synchronization and element geolocation problems are greater than those of a single platform-board opportunistic array. These problems will be addressed throughout the thesis.

Aside from the challenges, utilizing wireless beamforming in a swarm UAV network has many advantages over conventional beamforming techniques and may inspire some innovative applications.

C. PREVIOUS WORK

The concepts of opportunistic arrays and wireless beamforming are not new. The "opportunistic array" concept has been the focus of research and development undertaken by Loke [4]. Loke defines an opportunistic array as an integrated platform wide digital phased array, where the array elements are placed at available open areas over the entire surface of the platform. The elements of the opportunistic array are self-standing digital transmit/receive (T/R) modules with no hardwire connections other than primary power. Element localization and synchronization signals, beam control data, and digitized target return signals and all others associated with beamforming are passed wirelessly between the elements and a central signal processor [4].

Wireless beamforming (also referred as distributed beamforming) has attracted much interest for decades. Many researches have focused on several challenges such as element localization and synchronization of the elements in time and phase.

These problems are widely addressed for fully localized elements. The most frequent application is distributed beamforming in an array distributed over a platform surface, such as a ship. Loke [4] proposed possible solutions to element geolocation and synchronization problems for such an array. Loke's study compares the performance of "brute force" and "beam tagging" synchronization techniques and presents a survey of position location techniques.

Another NPS thesis by Chan [5] examines distributed beamforming in man portable communication networks. Chan's study, which considers a Personal Role Radio (PRR) system as a man portable communication network, is among the few to model mobile network elements for distributed beamforming. Nevertheless, considering various network configurations with predetermined element displacements while addressing the geolocation problem, it takes a quasi-static approach to the mobile network.

Considering the information transmission from a cluster of adjacent antennas to a distant stationary antenna, Tu and Pottie [6] have analyzed two network synchronization approaches: mutual synchronization and master-slave synchronization. The master-slave synchronization fits the objectives of beamforming in a swarm UAV network better than the mutual synchronization approach. A brief summary of synchronization techniques is presented in Chapter IV.

In an attempt to treat the problem of energy efficient communication in wireless *ad hoc* and sensor networks, Mudumbai, Barriac and Madhow [7] try to explore the feasibility of distributed beamforming in wireless networks. They also present a master-slave protocol for synchronization and investigate the feasibility of distributed beamforming with imperfect synchronization. Their claim is that even with imperfect synchronization of elements in a wireless network, a large fraction of the beamforming gains still exist given that the phase synchronization errors between the master and slaves are relatively small.

Ochiai, Mitran, Poor and Tarokh [8] utilize a probabilistic approach while analyzing the achievable performance of collaborative beamforming in distributed sensor networks. In their analysis model, the sensors form an *ad hoc* network and a two-dimensional disk of a given radius over which all elements are distributed uniformly presents as the network element distribution geometry. Their conclusion is that using N collaborative sensor nodes, a directivity of order N can be achieved asymptotically.

D. THESIS SCOPE AND OUTLINE

1. Defining the Problem Domain

This thesis treats the problem of collective transmissions in a swarm UAV network as distributed beamforming in a wireless network. In this approach, the single UAVs are treated as individual antenna elements and the swarm is defined in a wireless network domain. The thesis scope includes possible solutions to the main challenges in realizing wireless beamforming in a swarm UAV network and several military applications.

2. Primary Research Questions

This thesis aims to address several fundamental research questions in the context of wireless beamforming and swarm UAV network concepts.

a. How can distributed beamforming and opportunistic array concepts be applied to UAV swarms?

b. Can we use UAV-borne array elements within a UAV swarm collectively and utilize the digitally formed beam for operational purposes? Under what conditions is this feasible?

c. What are the technical challenges in implementing collective beamforming, and what are possible solutions to these challenges?

3. Thesis Organization

Chapter I presents the motivation of the thesis and gave a brief summary of the previous work done.

Chapter II introduces the wireless communication model for beamforming in a swarm UAV network along with an introduction of both wireless beamforming and UAV swarming concepts. The geometry of the problem is defined within a system study and two way link equations between a UAV network and a base station are derived.

Chapter III presents the previous applications of distributed beamforming and suggests new applications associated with distributed wireless beamforming in swarm UAV networks. An EA jamming application for both coherent and non-coherent operation is analyzed in detail. Operational advantages of the suggested applications are also discussed.

Chapter IV provides a feasibility analysis of wireless beamforming in UAV networks. The basic requirements, major challenges and possible solutions for the outstanding challenges are discussed.

Chapter V gives the conclusion of the thesis and recommends areas for future work.

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II. SYSTEM STUDY FOR WIRELESS BEAMFORMING IN A SWARM UAV NETWORK

A. WIRELESS BEAMFORMING AND SWARM UAVS

Wireless beamforming is defined as a spatial signal processing technique in Chapter I. More generally, beamforming can be defined as the use of multiple individual antennas for transmitting or receiving the same electromagnetic wave [5]. The major difference between classical beamforming by antenna arrays and distributed wireless beamforming is that whereas the geometry of the former is usually known *a priori*, the exact location of the sensor nodes in *ad hoc* networks is not, and it should be acquired dynamically [8].

As mentioned before, distributed beamforming applications in various different platforms have already been analyzed by many researchers. In most cases, when the fundamental problems of wireless beamforming are studied, the location of the nodes are considered to be known exactly or at least to an acceptable level of accuracy such that location errors are less than a fraction of the wavelength (usually $\lambda / 10$).

This study aims to analyze wireless beamforming performance in a swarm UAV network. For system level studies the exact locations of the nodes are considered to be known, while the performance without the exact location knowledge is treated separately. The performance of wireless beamforming without exact location knowledge is addressed similar to the collaborative beamforming in randomly distributed array systems.

B. DESIGN AND SYSTEM ARCHITECTURE

1. Single UAV Model

In order to realize beamforming in a wireless UAV network, the size and specifications of a single node needs to be addressed. In order to gain maximum advantage of low observability, it is useful to have the smallest possible UAVs as the elements of the anticipated swarm network. Having a very low emitted power will give the single UAV element a low probability of intercept.

Two examples for individual swarm UAV elements are introduced in Chapter III while analyzing the beamforming performance at the application level. For the purposes of this chapter more general assumptions and requirements of a swarm UAV beamforming network element will be given.

An advanced UAV architecture for a single element of a swarm UAV network presented in [25] is shown in Figure 3.

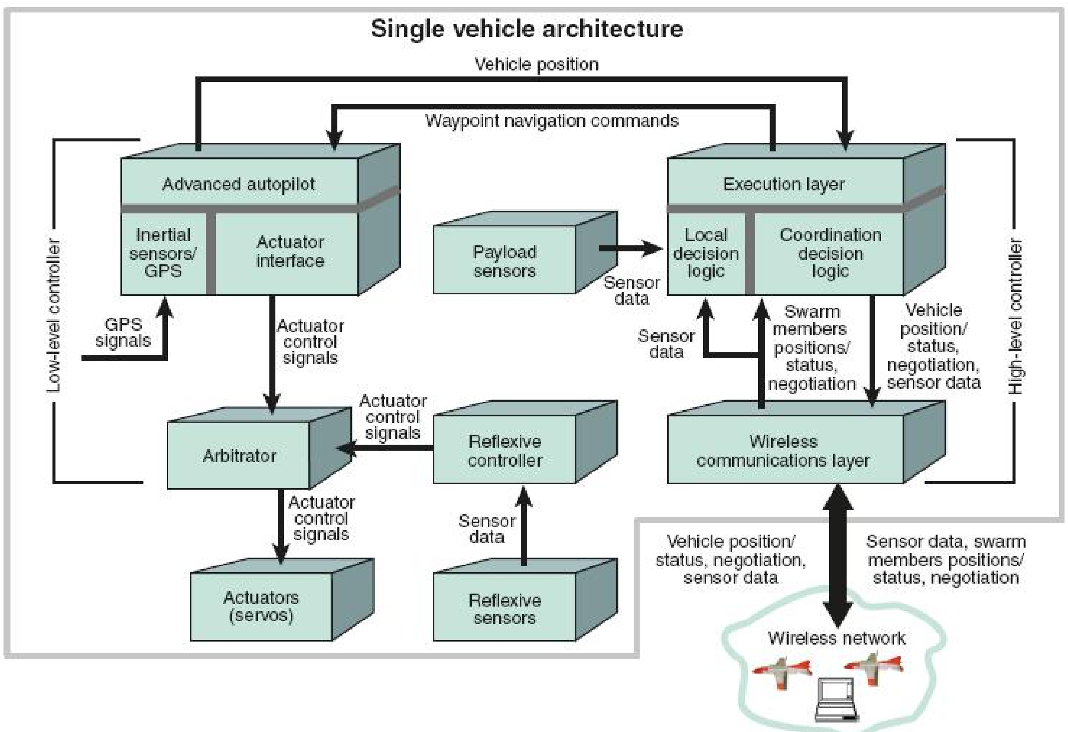

Figure 3. Single UAV architecture in a generic sense (From [25]).

The advanced autopilot, shown in Figure 3, together with a reflexive controller takes priority control of the vehicle for purposes of collision avoidance, formation flying, and terrain following. An arbitrator block is used to arbitrate autopilot and reflexive control signals. Together, these modules form an advanced controller that will allow the UAV to more effectively support the complex missions enabled by swarming techniques. Multiple UAVs operating cooperatively expand greatly on the capability of individual vehicles. However, the full utility of a UAV swarm will only be realized if they can operate autonomously: able to fly, adapt, communicate, negotiate, and carry out missions with no human in the loop [25].

The following assumptions for the single UAV element are considered;

(a) The single UAV is considered to be a small enough to be hand launched.

(b) The single UAV has an onboard antenna and a self-standing digital transmit/receive (T/R) module.

(c) Every single UAV is powered on its own and the digital transmit/receive (T/R) module onboard has its own local oscillator.

(d) A capability to synchronize all local oscillators to a common "master" clock is considered.

(e) The single UAV antennas are considered to have isotropic radiation patterns.

(f) The UAVs are connected by a wireless network capable of transmitting data and commands with negligible latency.

2. The Swarm

The swarm network is the wireless communication enabled domain where the problem of distributed beamforming of UAVs is defined and analyzed. Defining the swarm and swarm behavior will make the concept more understandable.

a. Swarming and Swarm Behavior

A swarm is defined in [23] as a collection of autonomous individuals, relying on local sensing and reactive behaviors, interacting such that a global behavior emerges from the interactions. Swarming is defined as an emergent behavior of simple autonomous individuals according to [23] in a general sense.

The concept of operations for a micro-UAV swarm system could be adopted from nature from the movement of flocking birds, a school of fish or swarming bees. The emergent behavior then will be the aggregate result of many simple interactions occurring within the flock, school or swarm [19].

b. Swarm Control

In order to achieve beamforming goals, control of the UAV swarm during the flight associated to the specific application is important. In an attempt to manifest an efficient strategy to control a UAV swarm for several different missions, Gaudiano, Shargel, Bonabeau and Clough [24] consider the following strategies:

(1) The *baseline strategy* is defined as a condition in which the UAVs are flying in a straight line until they reach the boundary of the determined area, at which time they turn to avoid exiting the area.

(2) The *random strategy* is similar to the baseline, but at each time step each UAV can change its heading by a small random angle.

(3) In the *repulsion strategy*, each UAV can sense other neighbor UAVs within a given radius, and it maneuvers so as to keep other UAVs outside of that repulsion radius.

(4) The *pheromone strategy* assumes that, whenever a UAV flies over a terrain cell, it leaves a marker indicating that the cell has been visited. Other UAVs are then able to determine, within a small local area immediately around them, whether cells have been visited or not. The UAVs then make small adjustments to their flight pattern to fly over unexplored cells.

(5) In the *global strategy*, it is assumed that the search space is divided into a number of large, square regions, and that a central controller monitors the level of coverage within each region, as well as the number of UAVs currently in that region [24].

Following the results of [24], the *pheromone strategy* is assumed to be the most effective strategy to control a UAV swarm in general cases.

For a wireless beamforming network within a UAV swarm, the *pheromone strategy* might be chosen given that the location data of each swarm element is passed accurately to the beamformer element. Otherwise the *baseline strategy* might be a more optimum choice, since it suggests a more stabilized flight path for the swarm elements. In each case a master UAV is designated to be the head of the swarm with necessary power and communication capabilities within the swarm network configuration.

These strategies are mostly used for functions such as searching. Once the swarm finds a victim radar, for instance in an EA application, the swarm control objectives change. The units might go into a pre-designated attack mode. They arrange themselves so as to maximize their lethality (e.g., maximum jamming power) and survivability. During the entire time in attack mode, a collective beam may have to be maintained. In other cases, different application dependent strategies might have to be utilized. The issues associated with the necessary strategy for the control of the swarm is not addressed in this study and left as a future work.

3. Transmission Equations for Swarm UAVs

In this section the free space transmission equations are derived for both the downlink (UAV to ground) and uplink (ground to UAVs). The geometry of the problem is presented in Figure 4.

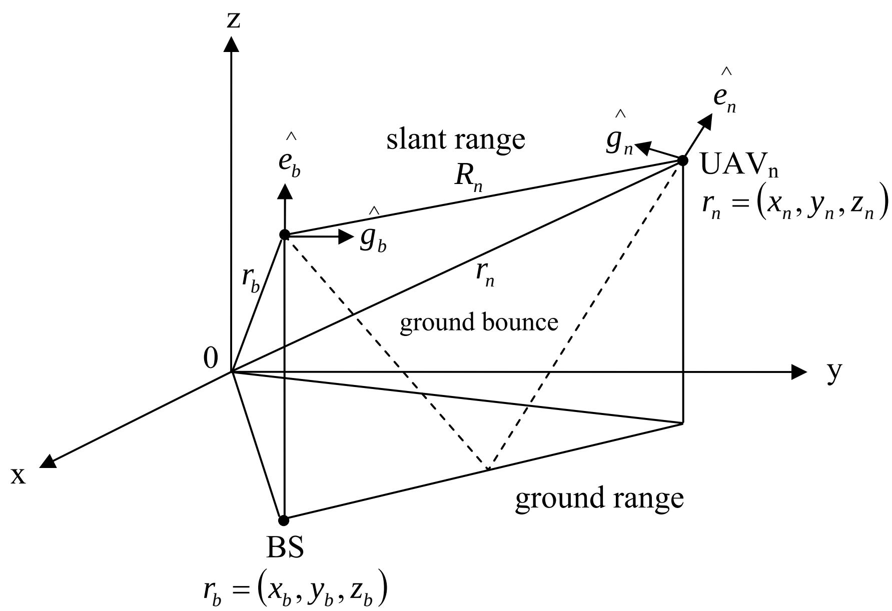

Figure 4. Geometry of the UAV swarm to/from base station communication model. (After [20])

In order to analyze the propagation characteristics from the swarm of UAVs to a radar or a base station (denoted as BS in the figure) and from the base station to the swarm, the communication model, shown in Figure 4, is considered in the Cartesian coordinates. The swarm elements are assumed to be distributed within the 3-dimensional Cartesian coordinate system while the *x*-*y* plane is taken as the ground plane. The origin of the Cartesian coordinate system is denoted as "0" and it is considered to be the phase reference. Mutual coupling effects among the UAVs are considered to be negligible. Positions of the base station and the n^{th} UAV are denoted as (x_b, y_b, z_b) and (x_n, y_n, z_n) respectively, so the position vectors for each can be written as:

Base station: $\bar{r}_b = \hat{x}x_b + \hat{y}y_b + \hat{z}z_b$

n^{th} UAV: $\bar{r}_n = \hat{x}x_n + \hat{y}y_n + \hat{z}z_n$

Polarization references for antennas:

Base station: $\hat{e}_b$

n^{th} UAV: $\hat{e}_n$

Direction of maximum antenna beams:

Base station: $\hat{g}_b$

n^{th} UAV: $\hat{g}_n$

Although the ground bounce can be significant, it is ignored in the following derivation. A path gain factor could be added to account for the ground bounce if necessary. In general, when a free space communication link between two antennas with an adequate separation distance of R, which is large enough for each antenna being in the far-field region of the other is considered, the received power at the receiving antenna is given by the Friis equation [21]

$$P_r = \frac{P_t G_t G_r \lambda^2}{(4\pi R)^2} \tag{2.1}$$

where:

P_t : Power transmitted,

P_r : Power received,

G_t : Gain of the transmitting antenna,

G_r : Gain of the receiving antenna,

λ : Wavelength corresponding to the communication frequency,

R : Distance between the antennas.

a. UAV Signal at the Base Station (Downlink)

Utilizing the above Equation (2.1) the received n^{th} UAV signal at the base station (P_{bn}) (downlink) can be expressed as:

$$P_{bn} = \frac{P_{tn} G_n(\theta_n) G_b(\theta_{bn}) \lambda^2}{(4\pi R_n)^2} |PLF_n|^2 \tag{2.2}$$

where P_{tn} is the transmitted power signal by UAV$_n$, R_n is the slant range of UAV$_n$ to the base station, $G_n(\theta_n)$ is the UAV$_n$ antenna gain in the direction of the base station and $G_b(\theta_{bn})$ is the base station antenna gain in the direction of the n^{th} UAV. For convenience a single angle variable (θ) is used but in general the patterns can be a function of two angle variables.

The polarization loss factor between the base station and the UAV$_n$ antenna is given by PLF_n in (2.2). For the polarization loss factor the following can be written:

$$|PLF_n|^2 = |\hat{e}_b \cdot \hat{e}_n|^2 \tag{2.3}$$

In order to obtain the total signal at the output of the base station antenna from all UAVs transmitting simultaneously, their individual voltages must be summed. It is convenient to use the antenna concept of effective height (also called effective length), which gives the voltage directly. The effective height of the base station (BS) antenna, which includes the polarization loss, can be expressed as:

$$\bar{h}_b = h_b \hat{e}_b \tag{2.4}$$

The open circuit voltage at antenna terminal n due to $\bar{E}_{bn}$ is given by

$$V_{oc_n} = \bar{h}_b \bullet \bar{E}_{bn} \tag{2.5}$$

The base station receiving antenna circuit is shown in Figure 5.

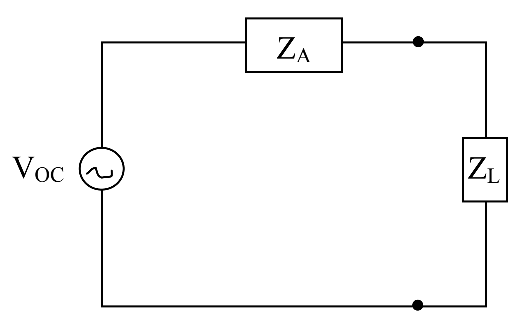

Figure 5. Receiving antenna circuit (After [20]).

In Figure 5, the antenna impedance is given by

$$Z_A = R_A + jX_A \tag{2.6}$$

and the resistance R_A is given by

$$R_A = R_r + R_l \tag{2.7}$$

where R_r is the radiation resistance and $R_l = 0$ (zero loss resistance) is assumed. By the use of a conjugate matched load ($Z_L = Z_A^*$) the circuit in Figure 5 can be simplified as shown in Figure 6.

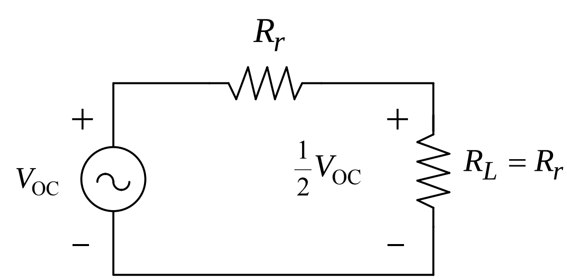

Figure 6. Base station receiving antenna circuit with conjugate matched load (After [20]).

Thus, when matched, the resistances in Figure 6 are equal ($R_r = R_L = R_A$). Since the voltage across R_L is equal to $\frac{1}{2}V_{oc}$, The power across the load can be written as;

$$P_L = \frac{V_{oc}^{\ 2}}{4R_L} \tag{2.8}$$

The effective height of the base station antenna is related to its effective area, and can be written as [21]

$$h_b(\theta_{bn}) = 2\sqrt{\frac{A_e(\theta_{bn})R_A}{\eta_0}} \tag{2.9}$$

The general relationship between gain (G) and effective area of an antenna (A_e) is given by

$$G = \frac{4\pi A_e}{\lambda^2} \tag{2.10}$$

So, the base station antenna gain in the direction of the n^{th} UAV can be written as a function of its effective area as follows:

$$G_b(\theta_{bn}) = \frac{4\pi A_e(\theta_{bn})}{\lambda^2} \tag{2.11}$$

Using Equation (2.11), Equation (2.10) can be rewritten to substitute for the angular dependent effective area as

$$h_b(\theta_{bn}) = 2\sqrt{\frac{R_A G_b(\theta_{bn})\lambda^2}{4\pi\eta_0}} \tag{2.12}$$

The power density W_{bn} in W/m^2 at the base station from UAV$_n$ is then given by

$$W_{bn} = \frac{1}{2\eta_0}|E_b|^2 = \frac{P_{tn}G_n(\theta_n)}{4\pi R_n^{\ 2}} \tag{2.13}$$

Using this, the electric field intensity $|E_{bn}|$ at the base station can be written as

$$|E_{bn}| = \sqrt{\frac{2\eta_0 P_{tn} G_n(\theta_n)}{4\pi R_n^{\ 2}}} \tag{2.14}$$

Adding the e^{-jkR_n} path phase shift and all other phases (such as synchronization, antenna, transmitter etc.), represented by $e^{j\phi_n}$, the above electric field intensity can also be expressed as a complex vector

$$\overline{E}_{bn} = \hat{e}_n |E_{bn}| e^{-jkR_n} e^{j\phi_n} \tag{2.15}$$

Then the voltage at the base station can be expressed as

$$V_{bn} = \frac{\overline{E}_{bn} \cdot \overline{h}_b(\theta_{bn})}{2} = \frac{1}{2}\left[\frac{2\eta_0 P_{tn} G_n(\theta_n)}{4\pi R_n^{\ 2}}\right]^{1/2} e^{-jkR_n} e^{j\phi_n} \hat{e}_n \cdot \overline{h}_b(\theta_{bn}) \tag{2.16}$$

If Equation (2.12) is substituted in Equation (2.16) for $\overline{h}_b(\theta_{bn})$, then the voltage at the base station from UAV$_n$ can be written in a general form as follows:

$$V_{bn} = \sqrt{\frac{2P_{tn}G_n(\theta_n)G_b(\theta_{bn})\lambda^2 R_A}{(4\pi R_n)^2}} e^{-jkR_n} e^{j\phi_n} \hat{e}_n \cdot \hat{e}_b \tag{2.17}$$

This equation gives the voltage of the n^{th} UAV transmitter at the output of the base station antenna.

b. *Total Signal at the Base Station Due to All UAVs*

In order to derive the expression for the total signal strength at the base station due to all the UAVs transmitting simultaneously, the following special case of (2.17) is considered:

(1) If all the UAV antennas are focused and perfectly synchronized, then $-jkR_n + \phi_n =$ Constant.

(2) If the UAV antennas are polarization matched with the base station antenna, then $\hat{e}_n \cdot \hat{e}_b = 1$.

(3) If all the UAVs have equal transmitter power and gain, then $G_n \equiv G_t$, $P_{tn} \equiv P_t$.

(4) If all the UAVs are in the same direction from the base station, then $G_b(\theta_{bn}) \equiv G_b$.

The total voltage at the base station from all of the UAVs is given by the summation of the individual UAV antenna voltages at the base station (across R_L in Figure 6). This sum can be expressed as follows:

$$V_{tot} = \sum_n V_n = \sum_n \bar{h}_b(\theta_{bn}) \cdot \frac{1}{2} \bar{E}_{bn} \tag{2.18}$$

$$V_{tot} = \sum_n V_{bn} = \frac{\sqrt{2\lambda^2 R_A}}{4\pi} \sum_n \sqrt{P_{tn}G_n(\theta_n)G_b(\theta_{bn})} \frac{e^{-jkR_n}}{R_n} e^{j\phi_n} \hat{e}_n \cdot \hat{e}_b \tag{2.19}$$

For the conditions listed in (1) to (4) above, and all the UAVs being approximately at the same range ($R_n \equiv R$) Equation (2.19) can be rewritten as:

$$V_{tot} = \frac{\sqrt{2\lambda^2 R_A P_t G_t G_b}}{4\pi R} N \tag{2.20}$$

Then the power at the load is given by

$$P_L = \frac{1}{2}\frac{|V_{tot}|^2}{R_A} = \frac{P_t G_t G_b \lambda^2}{(4\pi R)^2} N^2 \tag{2.21}$$

This agrees with the Friis equation for *N* identical coherent sources.

c. *Base Station Signal at UAV$_n$ (Uplink)*

Using the notation in Figure 4, the received signal at UAV$_n$ from the base station can be expressed similarly to Equation (2.2) as follows:

$$P_{rn} = \frac{P_{tb} G_b(\theta_{bn}) G_n(\theta_n) \lambda^2}{(4\pi R_n)^2} |PLF_n|^2 \tag{2.22}$$

where P_{tb} is the transmitted power by the base station antenna, R_n is the slant range of UAV$_n$ to the base station, $G_n(\theta_n)$ is the UAV$_n$ antenna gain in the direction of the base station and $G_b(\theta_{bn})$ is the base station antenna gain in the direction of the n^{th} UAV.

In order to process all of the UAV signals received from the BS coherently, a phase term ψ_n added at the BS must be included. The base station field at UAV$_n$ is given by

$$\bar{E}_n = \sqrt{\frac{2\eta_0 P_{tb} G_b(\theta_{bn})}{4\pi R_n{}^2}} e^{-jkR_n} e^{j\psi_n} \hat{e}_b \tag{2.23}$$

where the terms are similar to those used in downlink.

The voltage at the UAV$_n$ antenna terminal can be obtained directly using the effective height of the UAV antenna $\bar{h}_{en}$ as follows:

$$V_n = \bar{E}_n \bullet \bar{h}_{en} \tag{2.24}$$

$$V_n = \sqrt{\frac{P_{tb} G_n(\theta_n) G_b(\theta_{bn}) R_A}{2\pi}} \frac{\lambda}{R_n} e^{-jkR_n} e^{j\psi_n} \hat{e}_b \cdot \hat{h}_{en} \tag{2.25}$$

d. *Phase Coherence Analysis*

In this development the power equations for coherent and non-coherent transmission will be derived, and Equation (2.21) will be shown as a special case when the downlink is considered. When the transmitter phases for the swarm of elements are considered to be independent and identically distributed (iid) random variables, the expected power at the base station antenna can be written as follows:

$$\langle P_L \rangle = \frac{1}{2} \frac{\langle V_{tot} V_{tot}^{*} \rangle}{R_A} \tag{2.26}$$

where $\langle . \rangle$ denotes the expected value operator. Taking ϕ_n in Equation (2.19) as a uniformly distributed variable over $[-\pi, \pi]$, the variance of ϕ_n will be:

$$\mathrm{var}(\phi_n) = \frac{(2\pi)^2}{12} \tag{2.27}$$

while its mean will be:

$$\mathrm{mean}(\phi_n) = 0 \tag{2.28}$$

Using Equation (2.17) in Equation (2.26) gives

$$\langle P_L \rangle = \frac{P_t G_t G_b \lambda^2}{(4\pi)^2} \sum_m \sum_n \frac{e^{-jk(R_n - R_m)}}{R_n R_m} \langle e^{j(\phi_n - \phi_m)} \rangle \tag{2.29}$$

The two independent and identically distributed random variables of the phase term can be defined as one separate new random variable with variance $\overline{\Delta}^2$ as follows:

$$\Delta = \phi_n - \phi_m \tag{2.30}$$

Then, using Euler's identity, the phase term can be written as

$$\langle e^{j\Delta} \rangle = \langle \cos \Delta \rangle + j \langle \sin \Delta \rangle \tag{2.31}$$

The new iid random variable Δ can be assumed to be Gaussian in the same limit, so the following simplifications may be made [20]:

(i) if $m = n$ then $\langle \cos\Delta \rangle = 1$ and $\langle \sin\Delta \rangle = 0$

(ii) if $m \neq n$ then $\langle \cos\Delta \rangle = e^{-\overline{\Delta^2}}$ and $\langle \sin\Delta \rangle = 0$ [20]

Considering the above conditions for m and n, and assuming that the UAVs are concentrated at a long range ($R_n \approx R_m \equiv R$), Equation (2.29) can be written as follows:

$$\langle P_L \rangle = \frac{P_t G_t G_b \lambda^2}{(4\pi)^2 R^2}\left[e^{-\overline{\Delta^2}} N^2 + \left(1 - e^{-\overline{\Delta^2}}\right) N\right] \tag{2.32}$$

where $e^{-\overline{\Delta^2}} N^2$ indicates coherent transmission and $\left(1 - e^{-\overline{\Delta^2}}\right) N$ indicates random (noncoherent) transmission.

For coherent transmission, there are no phase differences, so $\overline{\Delta^2} \cong 0$ and Equation (2.32) yields

$$\langle P_L \rangle = \frac{P_t G_t G_b \lambda^2}{(4\pi)^2 R^2} N^2 \tag{2.33}$$

This is the same result as Equation (2.21).

For non-coherent transmission, the phase differences are large, so $\overline{\Delta^2} \to \infty$ is assumed and Equation (2.32) yields

$$\langle P_L \rangle = \frac{P_t G_t G_b \lambda^2}{(4\pi)^2 R^2} N \tag{2.34}$$

This result occurs for N noncoherent transmitters, such as noise jammers. These results can also be extended to beamforming. Perfect synchronization and focusing yield Equation (2.33).

Using a Monte Carlo simulation for Equations (2.33) and (2.34), the comparison of the received power versus the number of transmitters is shown in Figure 7.

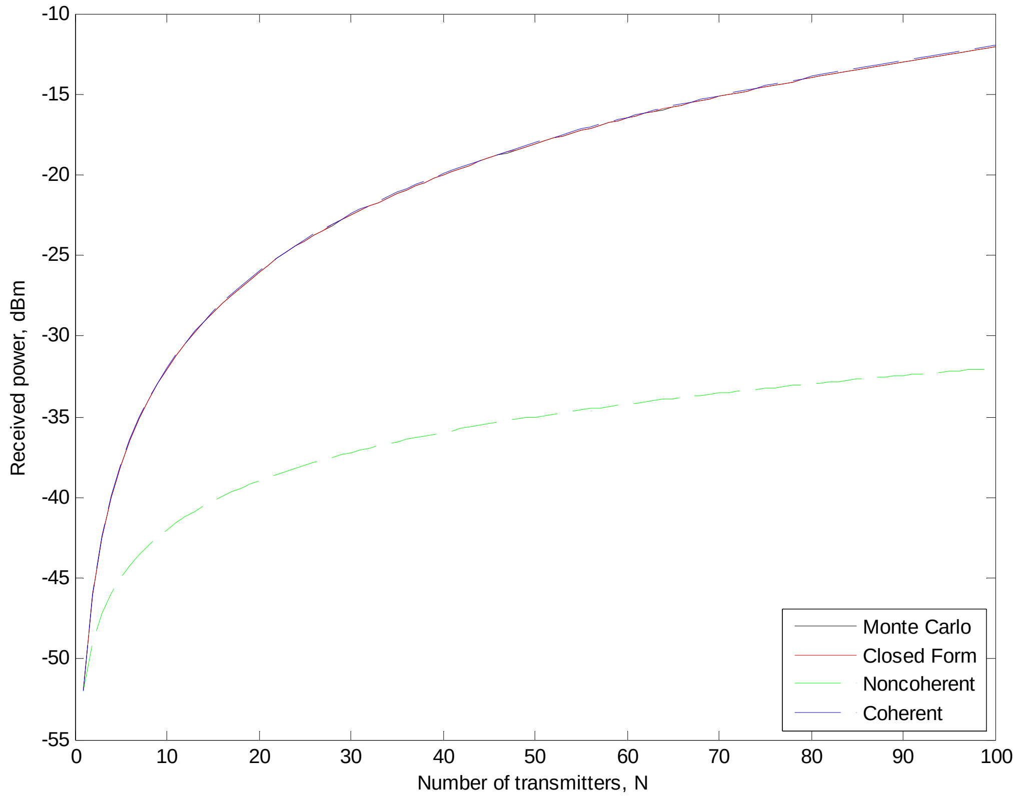

Figure 7. Monte Carlo simulation results with 100 trials at each value of *N*, RMS error = 1.0919 degrees.

Figure 7 shows a case where the desired RMS error is very low (approximately 1.1 degrees). So, the result of the Monte Carlo simulation is very similar to the perfect coherent integration result. For greater RMS errors the Monte Carlo curve will be less steady. Figure 8 shows the same simulation results with a relatively large RMS error of approximately 80 degrees.

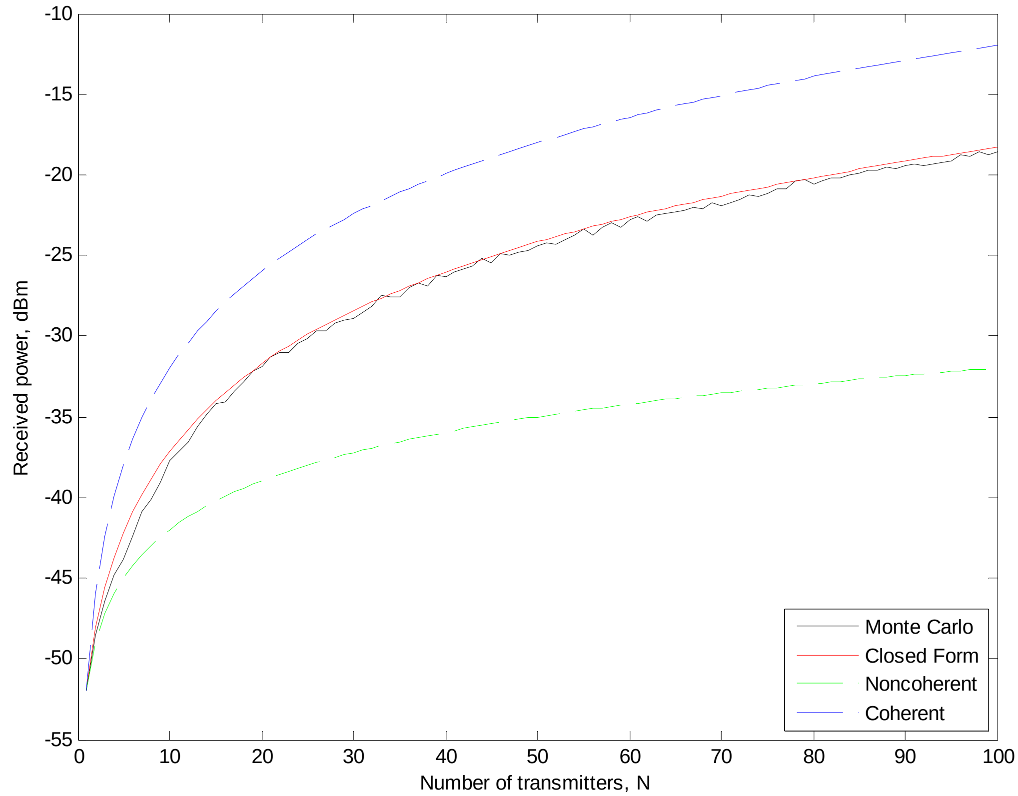

Figure 8. Monte Carlo simulation results with 100 trials at each value of *N*, RMS error = 79.8187 degrees.

As seen in Figure 8, when relatively large phase errors are present, the received power is clearly lower than the perfect coherent integration case.

4. Distributed Beamforming in a UAV Swarm

An array beamformer circuitry multiplies the output of *N* antenna array elements by a set of *N* complex weights and sums the results. These complex weights can be adjusted so as to achieve the desired beam direction [22]. In a UAV swarm, beamforming is done wirelessly (collaborative or collective beamforming). A general block diagram for wireless beamforming is shown in Figure 9.

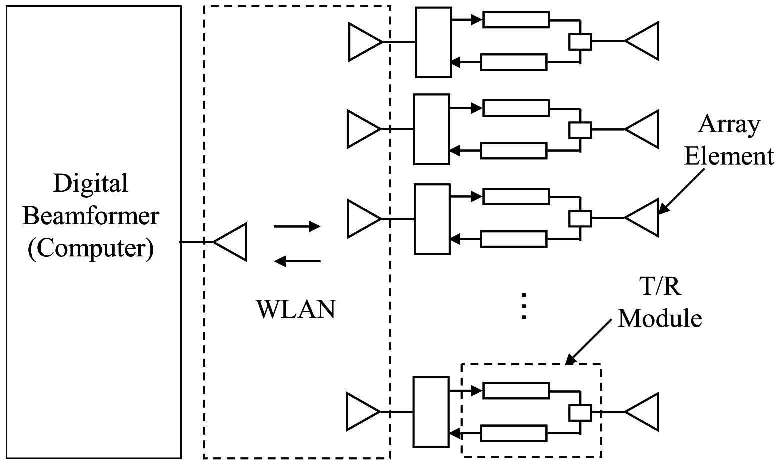

Figure 9. Wireless beamforming network (After [2]).

Collective beamforming for the uplink and the downlink are illustrated in Figures 10 and 11, respectively. When the UAVs are receiving, as shown in Figure 10, the beamformer weights the voltages in Equation (2.25) by a set of weights $\{W_1, W_2, .., W_n\}$ in order to obtain a maximum by constructive interference [5]. The processor can be located on a separate, dedicated UAV, or it might simply be one designated member of the swarm. The communication between the UAVs and controller (or master) is done by a wireless network, as indicated in Figure 9. The α_i in Figures 10 and 11 are attenuation constants for path losses, if present.

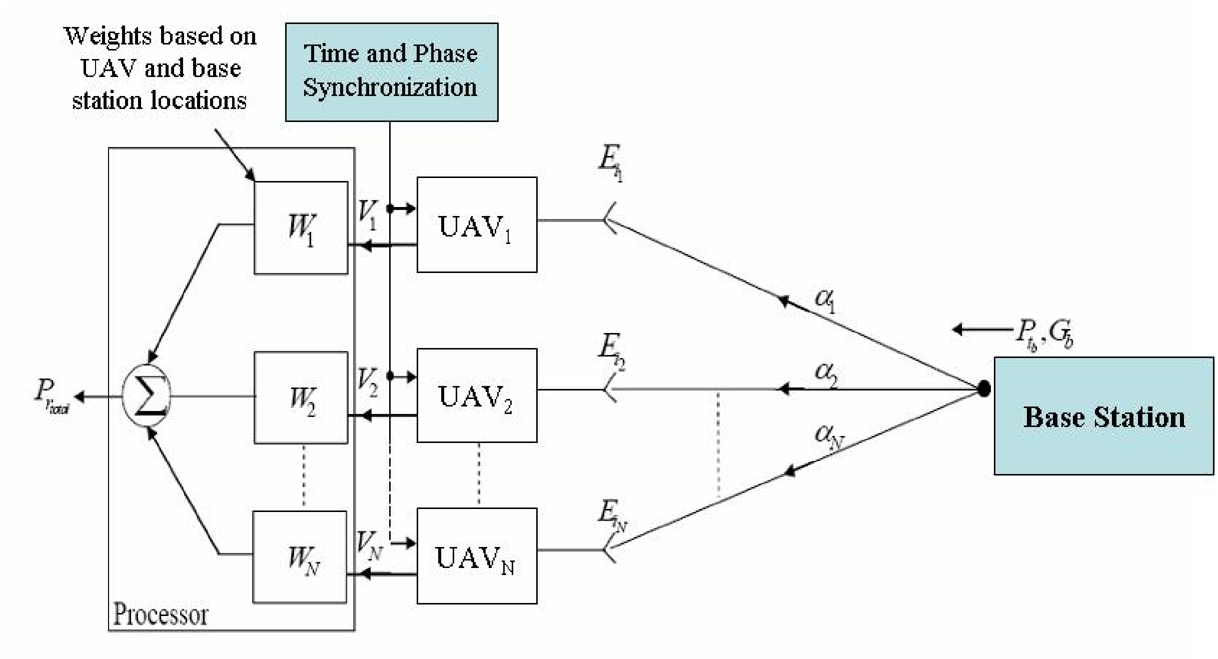

Figure 10. Collective beamforming for the uplink (After [5]).

When the UAVs are transmitting, as shown in Figure 11, all the UAV antennas within the swarm transmit simultaneously with proper time and phase delays so that all the UAV signals arrive at the base station antenna in phase at the same time [5]. For the downlink, the received power is given by Equation (2.32) and for coherent waveforms the result in Equation (2.33) is achieved. When the swarm is considered to be a single transmitter array and its performance is compared to that of a single UAV transmitter antenna, the results indicate an increase in received power by a factor of N^2.

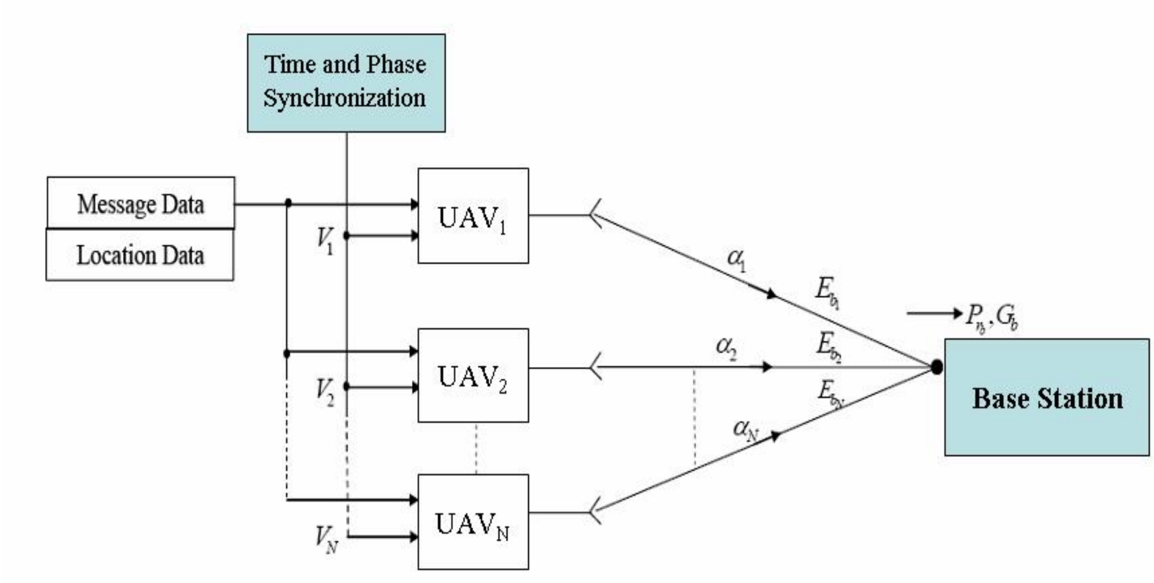

Figure 11. Collective beamforming for the downlink (After [5]).

This chapter presented a system study for distributed beamforming in a swarm UAV network. It included a general approach to modeling the single UAV element within the swarm while accounting for both coherent and non-coherent receive conditions. The last section of this chapter also derived the transmission equations while modeling the UAV swarm as a wireless beamforming network.

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III. OPERATIONAL APPLICATIONS OF OPPORTUNISTIC ARRAY OF UAVS

A. PRESENT MILITARY APPLICATIONS OF OPPORTUNISTIC ARRAYS AND WIRELESS BEAMFORMING

Opportunistic arrays and wireless beamforming are applied within many warfare battlespaces for different purposes. Radar and communications are two major areas of interest for much of the research conducted on these concepts. The most frequent use of opportunistic arrays is the digital phased array radar application, which is mostly used for long range detection purposes. Loke [4] considers a shipboard opportunistic array where the array elements are placed at available open areas over the ship surface. An example of a shipboard opportunistic array was shown in Figure 1 in Chapter I. Such an array is often called as wirelessly networked opportunistic digital array radar (WNODAR).

One of the key applications for the WNODAR is in ballistic missile defense (BMD). This application is based on early detection and tracking of adversary ballistic missiles from long ranges. The WNODAR has many advantages over conventional phased array radars. As a digital phased radar, it is capable of multiple simultaneous receive beams. Rapid dynamic reconfiguration of output beams is possible. Also, the digital architecture eliminates the need for analog beamforming components and their associated calibration and drift issues [4].

Another application of wireless beamforming is achieved by exploiting existing buildings or a hillside to form the surface of the opportunistic array. The elements distributed over a building or a hillside might constitute a hastily formed phased array. With proper deployment such hastily formed radar networks can be used for either communications or air defense radars to detect and track targets missiles, aircraft or artillery rounds [9, 10].

The abovementioned applications consider single platform based wireless beamforming, or at least wireless beamforming is performed with fixed element locations. In some other applications the elements are considered to be mobile, such as individual troops or vehicles in motion. In [5] wireless beamforming in a man portable communication network is considered where the PRRs carried by individual troops are modeled as the elements of the distributed beamforming network. Figure 12 shows the application proposed in [5]. The collective beam formed by several radios transmitting (or receiving) simultaneously can extend the range of the system.

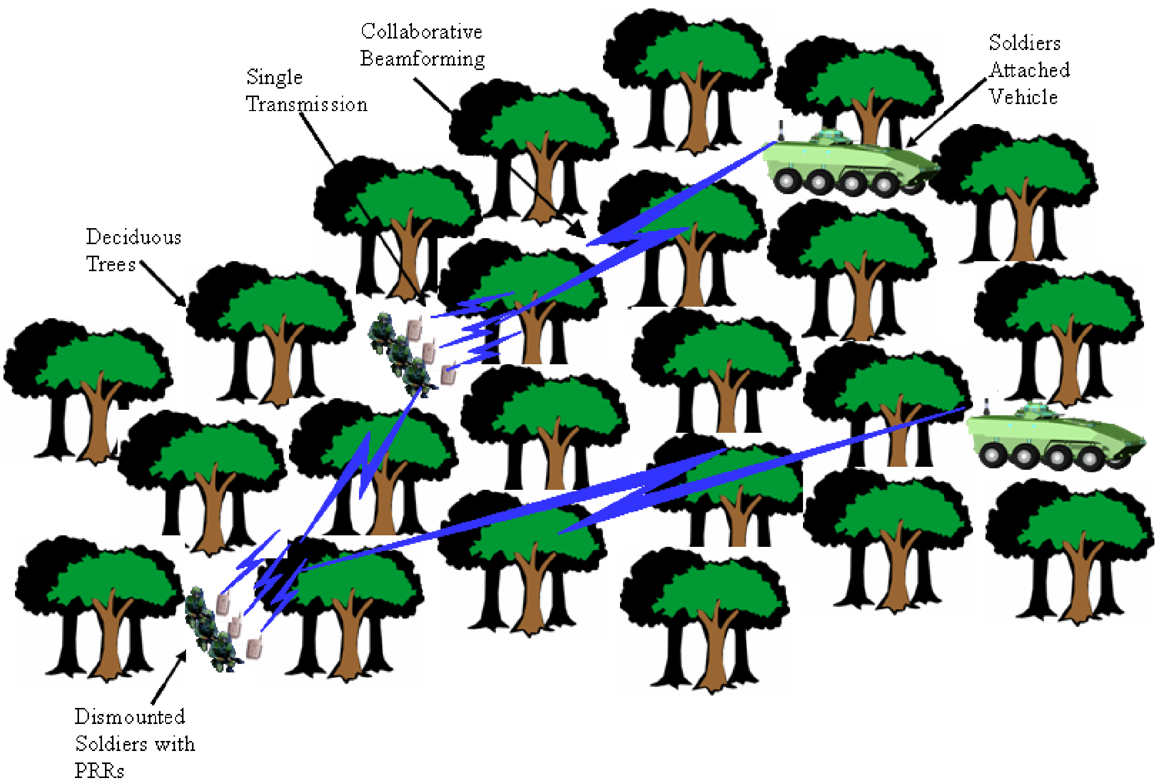

Figure 12. Collaborative beamforming in a man portable communication network (From [5]).

Another application of multi-platform based phased arrays is considered by Lee and Dorny [14]. In their study, digital beamforming is utilized within a self-survey technique to achieve self-calibration of large antenna phased arrays for both accurately known and approximately known element locations.

A multi-satellite high resolution imaging system and a multi-ship high resolution surveillance system, shown below in Figure 13, are among the applications of such large, randomly distributed multi-platform based arrays. The main goal in such applications is to obtain a higher angular resolution in comparison to single platform based phased arrays.

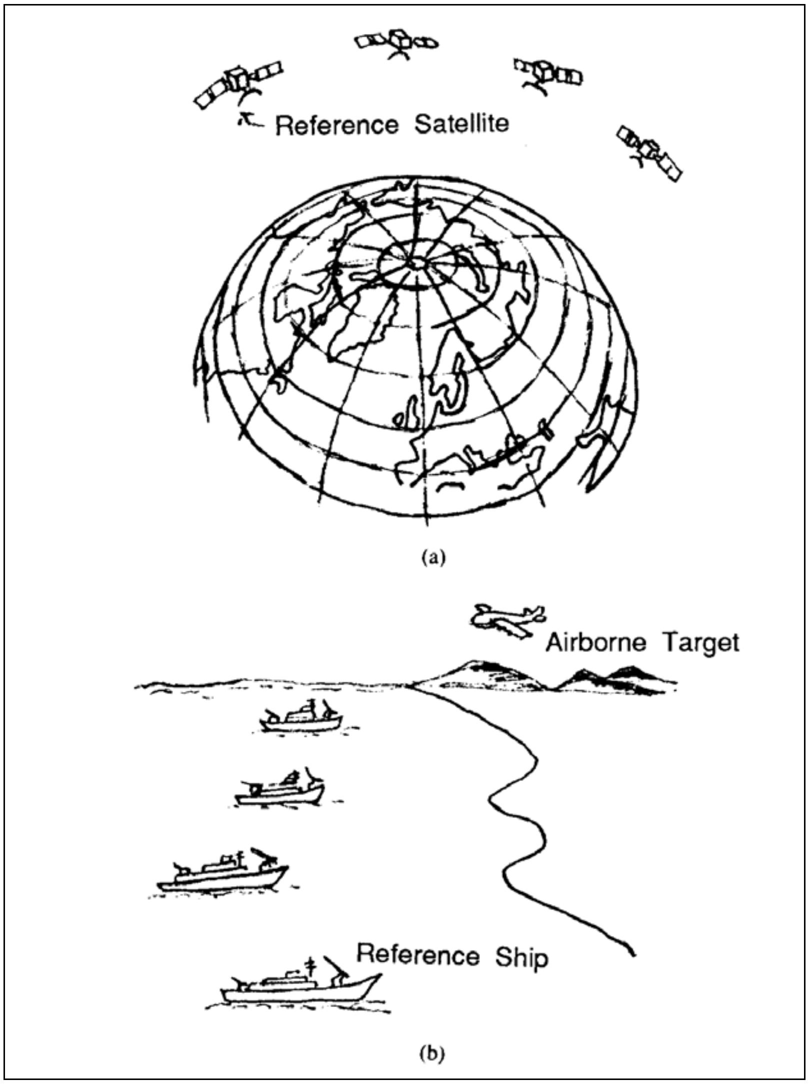

Figure 13. (a) Multi-satellite high resolution imaging system. (b) Multi-ship high resolution surveillance system (From [14]).

The applications shown in Figure 13 represent a close analogy to a UAV swarm beamforming network by means of mobile array elements.

B. PRESENT MILITARY APPLICATIONS OF UAVS

Similar to wireless beamforming, various applications of UAVs have also been used for military purposes. Table 1 lists some examples of how UAVs could be utilized within several kinds of warfare.

Top US Army Tactical UAV Missions (1999)		
Priority	**Mission**	**Payload Type**
1	Reconnaissance	EO / IR Search and Rescue (SAR)
2	Mine Countermeasures	Infra-Red (IR)
3	Target Designation	Laser Target Designators
4	Battle Management	EO / IR Search and Rescuer (SAR)
5	Chemical-Biological Warfare	Point-Source Detectors
6	Signals Intelligence (SIGINT)	COMINT / ELINT (Communication & Electronic Intelligence)
7	Counter-Camouflage	Multi-Spectral Sensors
8	Electronic Warfare (EW)	Electronic Surveillance Measures / Jammers
9	Combat Search and Rescue	EO / IR COMINT
10	Communications Data Relay	Communications Relays
11	Information Warfare (IW)	Specialized Electronick Attack (EA)

Table 1. US Army tactical UAV missions (After [13]).

Table 1 also shows the payload types for each associated mission type. Though Table 1 shows only the application types used by US Army, it is a useful example to demonstrate the wide scale of applications of the UAV concept over any kind of warfare type.

UAVs may be included in other warfare types as well. According to [11], the possible military missions carried out or supported by UAVs include:

- Intelligence, Surveillance, and Reconnaissance (ISR)

- Command and Control (C2)/ Communications
- Force Protection (FP)
- Signals Intelligence (SIGINT)
- Weapons of Mass Destruction (WMD)
- Theater Air and Missile Defense (TAMD)
- Suppression of Enemy Air Defenses (SEAD)
- Combat Search and Rescue (CSAR)
- Mine Counter Measures (MCM)
- Meteorology and Oceanography (METOC)
- Counter Narcotics (CN)
- Psychological Operations (PSYOP)
- All Weather/ Night Strike
- Exercise Support
- Counter Fire
- Anti-Submarine Warfare (ASW)
- Navigation

While all types of UAVs have a wide scale of usage within numerous types of military missions, for the purposes of this study the focus will be on electronic warfare and ISR applications.

1. Use of UAVs in EW Applications (Electronic Attack)

Use of UAVs in EA missions is relatively new. In the traditional approach, EA involved specially designed manned aircraft such as the Navy EA-6B Prowler and the Air Force EF-111 Raven. Because UAVs can achieve theoretically higher levels of survivability than manned aircraft, they offer a desirable alternative for conducting EA missions to manned aircraft. Small or mini UAVs are also well suited for EA missions due to their small size. Their stealthy nature makes them less susceptible to detection and more likely to get close to the adversary radar systems [12].

2. Use of UAVs in ISR Applications

Today, Intelligence, Surveillance, and Reconnaissance (ISR) are by far the predominant missions of UAVs. ISR missions can be described in terms of three categories [12]:

a. Standoff Missions

Standoff missions are usually conducted during peacetime. They are also used when the probability of vehicle loss or political ramifications are too great to risk the exposure of the UAV to detection. To achieve the effect of persistence, the UAV must have the capability to remain on station for long periods of time. Often broad areas need to be covered, requiring high altitude flights with long range sensor performance. In these cases, larger UAVs capable of long endurance and the ability to carry heavier payloads are needed [12].

b. Overflight Missions

Overflight missions occur with or without the knowledge and/or consent of another state or entity being monitored. The UAV may fly at high, medium or low altitudes depending on the particular situation. If persistence is needed and image resolution or signal collection can be accomplished from high altitude, then a larger high altitude long endurance (HALE) platform such as the Global Hawk or Predator could be chosen. If poor weather prevents operation from high or medium altitude then a small unmanned aerial system (SUAS) could be utilized. There is no particular standard platform used for overflight missions as there are for standoff and denied access missions [12].

c. *Denied Access Missions*

Denied access missions are generally used in support of combat operations or national security requirements. In many cases satellites can be used, but the disadvantage with satellites is their predictability [12]. The main advantage of using UAVs, particularly small UAVs, is that they have lower observability and the associated risk is significantly lower.

C. POSSIBLE APPLICATIONS OF UAV-BORNE OPPORTUNISTIC ARRAYS

The diversity of wireless beamforming applications over military systems and operations is due to potential improvements achieved in both radar and communications parameters such as range and efficiency. Given that the specific problems associated with beamforming in UAV networks are properly addressed, these improvements will yield similar improvements in UAV network applications. Furthermore, specific advantages are gained due to the mobile structure of the UAV network.

Throughout the analysis of possible opportunistic array applications over UAV networks, small sized UAVs will be predominately considered. Actually the terms such as "small UAVs," "mini UAVs" and "micro-UAVs" have slightly different definitions and specified size limits. As an example, Defense Advanced Research Projects Agency (DARPA) defines a micro-air vehicle (MAV), as a UAV measuring less than 15 cm in any dimension while carrying a miniaturized payload, simple avionics, and a communication link [26]. For the purposes of this study, these terms will be used interchangeably.

1. Electronic Attack Jammer Application

a. *Availability of the EA Payloads for Small Sized UAVs*

Several examples discussed in this section show that EA payloads are available for small sized UAVs. The RQ-16A Micro-air vehicle (MAV) and Aerosonde mini UAV are two examples of small sized UAVs capable of carrying EA payloads.

Figure 14. The RQ-16A Micro-air vehicle (From [15]).

The RQ-16A MAV shown in Figure 14 was developed as a back-packable, fully autonomous, vertically launched-and-landed ducted fan UAV capable of providing electro-optical or infrared hover-and-stare support to the dismounted soldier. The MAV is small (less than 14-inch duct outer diameter), flies autonomously, has an endurance of 55 minutes at sea level, and can operate at altitudes over 10,000 feet. These capabilities make it ideal for operations in the complex/urban terrain and extreme conditions typical of restricted military environments [15]. The specifications of RQ-16A MAV are summarized in Table 2.

Characteristics:

MAV			
Weight	15 lb	Payload	2 lb
Length	15 in	Engine Type	Heavy fuel piston
Wingspan	13-in duct diameter		

Performance:

Ceiling	10,500 ft	Endurance	~40 min
Radius	~6 nm		

Table 2. The RQ-16A MAV specifications (From [15]).

MAV payloads for electronic warfare functions are a possibility. Reference [16] gives information about an effort to develop a 14-gram (0.5-ounce) radar-jamming payload. The concept behind this approach is that the mission MAV would be delivered to the vicinity of the target by a larger, longer-range aircraft whereupon it would then seek out and fly to the victim radar. Then, the MAV would land on the radar near its receiver(s) and transmit its jamming energy. What the MAV would lack in transmit power would be made up in reduced range. A similar approach could also be used to jam radio frequency communications systems [16].

The Aerosonde mini UAV shown in Figure 15 is another candidate [17]. The Aerosonde Robotic Aircraft is one example of mini UAV systems that provide an increasing range of unique EW capabilities, which will present challenges to traditional EW doctrine. The Aerosonde is a low cost, high endurance UAV that has a number of unique characteristics.

The Aerosonde UAV was originally designed to provide economical weather reconnaissance in remote and dangerous areas. As such, the aircraft have limited redundancy features and are considered expendable.

Aerosonde UAVs began participating in meteorological field trials in 1995, and have since performed over 3500 hours for meteorological applications in Australia, North America, Japan and Taiwan. Table 3 identifies the current specifications of the Mark 3 Aerosonde.

Specification	
Weight / wing span	13-15 kg / 2.9 m
Engine	24 cc, fuel injected H type
Full Fuel Load	5 kg
Navigation	GPS, automatic front tracking
Max. Comm. Range	180 km depending on height and terrain
On board power generation	Maxon generator provides 18 V DC at 1 Amp, 40 W continuous, 60 W peak, 30 W for payload
MTBF	250 hours
Operation	
Staff for Launch and Recovery	2-3: Controller, Engineer, Pilot/Maintenance
Ground & air communications	UHF or SatComms to/from Aerosonde, VHF to field staff and other aircraft, internet to command centre and customers.
Performance	
Speed / Climb	18 – 32 ms^{-1} / Climb >2.5 ms^{-1}
Endurance, Range	Weather mode 20 to 30 h, 2000 to 3000Km. (No wind range)
Altitude Range	100 m – >7000 m (intermediate weight)
Payload	Max 5 kg ~ 10 hour endurance. Max 2 kg ~ 30 hour endurance.

Table 3. Specifications of the Mark 3 Aerosonde mini UAV (After [17]).

This vehicle is autonomous and is easily programmed to perform desired missions for the end-user. The Aerosonde operates in a completely robotic mode with command being exercised by local operators or from a center that may be many thousands of kilometres away. The aircraft have been tested, and conducted operations, in a variety of conditions from the tropics to the Arctic and in all weather conditions.

Figure 15. The Aerosonde mini UAV (From [17]).

Communications between the aircraft and the ground station is achieved via UHF radio (ranges up to 150 km) and via Iridium Low Earth Orbit (LEO) satellite (over-the-horizon global coverage).

A number of EW payloads have already been developed for the Aerosonde UAV. They include:

- ES Superhet Receiver
- ES IFM Receiver
- EA Noise Jammer
- RF Repeater (Jammer Test Target)

The ES Superhet Receiver unit weighs in at 2.7 kg and operates in the frequency range 2-18 GHz. A separate datalink is used to transmit pulse descriptor words out to a range of 12 km. The unit is installed in the Aerosonde with switching between two antennas, each with a beamwidth of 180 degrees, as shown in the Figure 16.

Figure 16. Aerosonde UAV equipped with ES superhet (From [17]).

The ES IFM Receiver also operates in the 2-18 GHz band with an RF resolution of approximately 4 MHz. The unit weighs approximately 3 kg and requires 30 W of payload power. This payload uses the same datalink as the ES Superhet.

The EA Noise Jammer operates in two bands: High-band 8-12 GHz through tunable horns mounted in shields either side of the aircraft, and low-band 850-950 MHz through Yagi antennas mounted under the wings. The installation configuration is shown in Figure 17.

Figure 17. Aerosonde UAV equipped with EA jammer (From [17]).

The RF Repeater (Jammer Test Target) was developed to provide a target of selectable Radar Cross-Section to validate the masking performance of the jammer against a number of radars. The repeater can generate an apparent RCS of up to 10 m^2 and weighs 2 kg.

b. Analysis of Jamming Performance

In an EA jammer application the main purpose is to screen the friendly forces by preventing the detection capabilities of the adversary systems. The interdependent parameters include range of the jammer, range of the screened platform or platforms, radar cross section (RCS) of screened platform, jammer power, the maximum detection range of the victim radar and the signal-to-noise ratio required (SNR_{req}) at the victim radar. The SNR_{req} of the victim radar and its maximum detection range is dictated by the adversary system, and friendly forces can do nothing to change them. However, for detection of a jet aircraft, a 20 to 1 SNR (SNR_{req} =13 dB) might be required for a search radar [18].

The RCS of the screened aircraft changes according to the size, shape, material and other design characteristics. Figure 18 shows approximate RCS values for several aircraft.

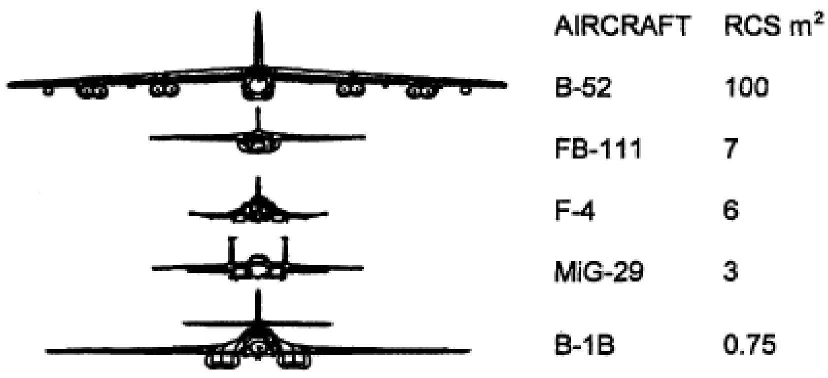

Figure 18. Notional RCS of military aircraft (From [18]).

Considering the data in Figure 18, a target RCS of 2 m^2 is used for a single aircraft. If the target to be screened is a formation of several aircraft instead of a single aircraft, the RCS will be higher.

The following standoff jammer (SOJ) scenario is considered for the analysis of the jamming performance of an EA UAV swarm over an air defense missile search radar, as depicted in Figure 19.

(1) A single aircraft with an RCS of $\sigma = 2\ \text{m}^2$ is considered as the friendly force to be screened. This aircraft will be sometimes called a “target” throughout the scenario. Target aircraft is at a range of R_t in the main lobe of the victim radar radiation pattern.

(2) Fan Song SA-2 search radar is considered as the victim radar. The Fan Song radar operates in the E-band (2-3 GHz) with a peak transmitter power of P_t. It has a maximum gain of G_0 in the main lobe and G_s at the angular direction of the jammer asset.

(3) An $SNR_{req} = 13$ dB is required for detection of the target at the victim radar.

(4) When the radar is being jammed, the jammer power is the noise, and the target distance yielding $SNR_{req} = 13$ dB is considered as the burnthrough range.

(5) Either a single UAV or a swarm of UAVs is considered as the jammer asset. The jammer asset is at a range of R_j in a side lobe of the victim radar radiation pattern.

(6) A single jammer UAV transmits a jamming power of P_j with a gain of G_j.

(7) For multiple UAV cases, all of the swarm elements are considered to be virtually at the same range and in the same angular region of the victim radar radiation pattern.

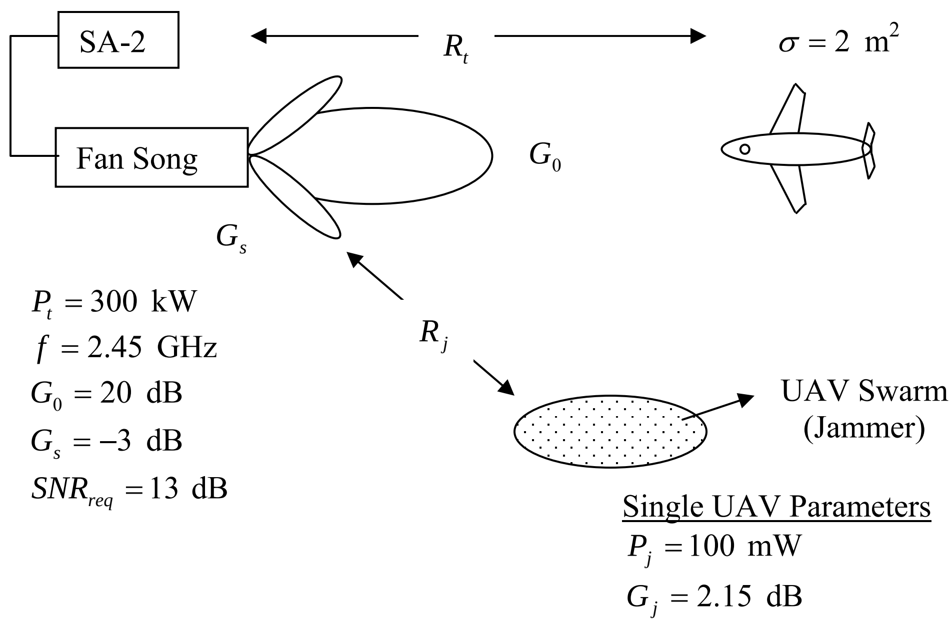

Figure 19. SOJ scenario with an SA-2 Fan Song search radar.

The burnthrough range for a jammer is generally defined as the range at which its signal is equal to the target return signal-to-jam ratio (*SJR* =1). But, this is a general approach to the jamming effectiveness. For an effective detection, following [18], $SNR_{req} = 13$ dB will be used for the air defense radar. For analysis purposes the *SJR* at the victim radar will be considered for *SNR*. This approach yields a threshold value of $SJR_{req} = 13$ dB at the victim radar for detection of the target.

The value of SJR_{req} at the victim radar helps to determine the required jamming power-to-signal ratio (JSR_{req}) at the victim radar for the jamming to be effective. The relation between these to threshold values is given by

$$JSR_{req} = \frac{1}{SJR_{req}} \tag{3.1}$$

Thus the JSR_{req} value for the scenario is 0.05.

The JSR at the victim radar can be written as follows:

$$JSR = \frac{P_{J_R}}{P_{S_R}} \tag{3.2}$$

P_{J_R} : Jamming power received at the victim radar

P_{S_R} : Target return received at the victim radar

While P_{J_R} is calculated as a one way link, P_{S_R} should be calculated as a two way link. Using the radar range equation [28] and assuming equivalent bandwidths for the jammer and the victim radar, the powers can be written as follows:

$$P_{J_R} = \frac{P_j G_j G_s \lambda^2}{\left(4\pi R_j\right)^2} \tag{3.3}$$

$$P_{S_R} = \frac{P_t G_0{}^2 \lambda^2 \sigma}{\left(4\pi\right)^3 R_t^2} \tag{3.4}$$

Thus, substituting (3.3) and (3.4) in (3.2), JSR yields

$$JSR = \frac{P_j G_j G_s 4\pi R_t{}^4}{P_t G_0{}^2 \sigma R_j{}^2} \tag{3.5}$$

As mentioned before, the threshold value of JSR, which is denoted as JSR_{req}, gives the burnthrough range (R_{BT}). Rearranging (3.5) with JSR_{req}, R_{BT} is expressed as follows:

$$R_{BT} = \left(\frac{JSR_{req} P_t G_0{}^2 \sigma R_j{}^2}{P_j G_j G_s 4\pi}\right)^{1/4} \tag{3.6}$$

Using (3.6), a single jammer UAV at $R_j = 500$ m gives a burnthrough range of $R_{BT} = 3473$ m while at $R_j = 1000$ m gives $R_{BT} = 4912$ m.

Figure 20 presents the relationship between the target range (R_t) and the achieved JSR for both $R_j = 500$ m and $R_j = 1000$ m. The figure also shows the (-13 dB) threshold value JSR_{req} and its intersection with the achieved JSR curves gives the burnthrough ranges (R_{BT}) for both jammer cases with the system parameters as specified in Figure 19. The area below the JSR_{req} line is considered as the detection region, while the area above it is considered as the effective jamming region.

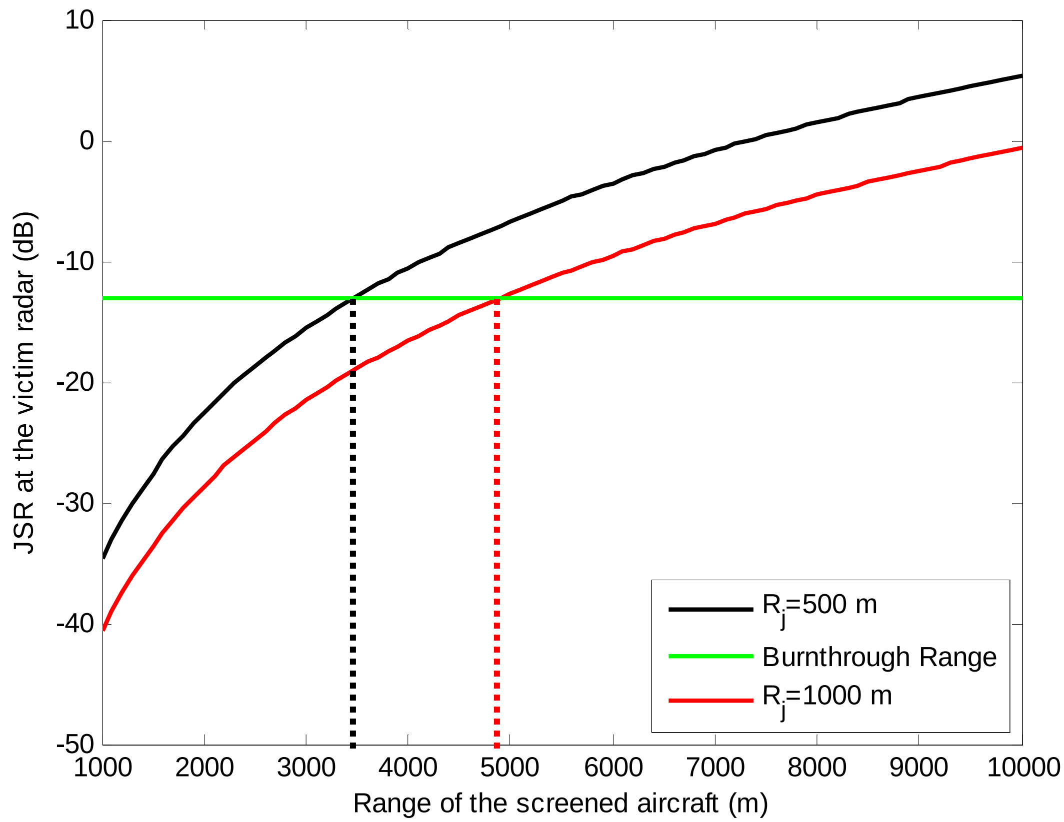

Figure 20. Detection characteristics of SA-2 Fan Song radar vs. single jammer UAV.

Several variations of the above scenario with multiple UAVs (representing a swarm) are also considered. The number of the UAVs is increased one by one up to 10. For coherent jamming the total power increases as N^2 as developed previously in Equation (2.33). The resulting burnthrough ranges (R_{BT} s) vs. the number of swarm elements for both $R_j = 500$ m and $R_j = 1000$ m jammer ranges are presented in Figure 21.

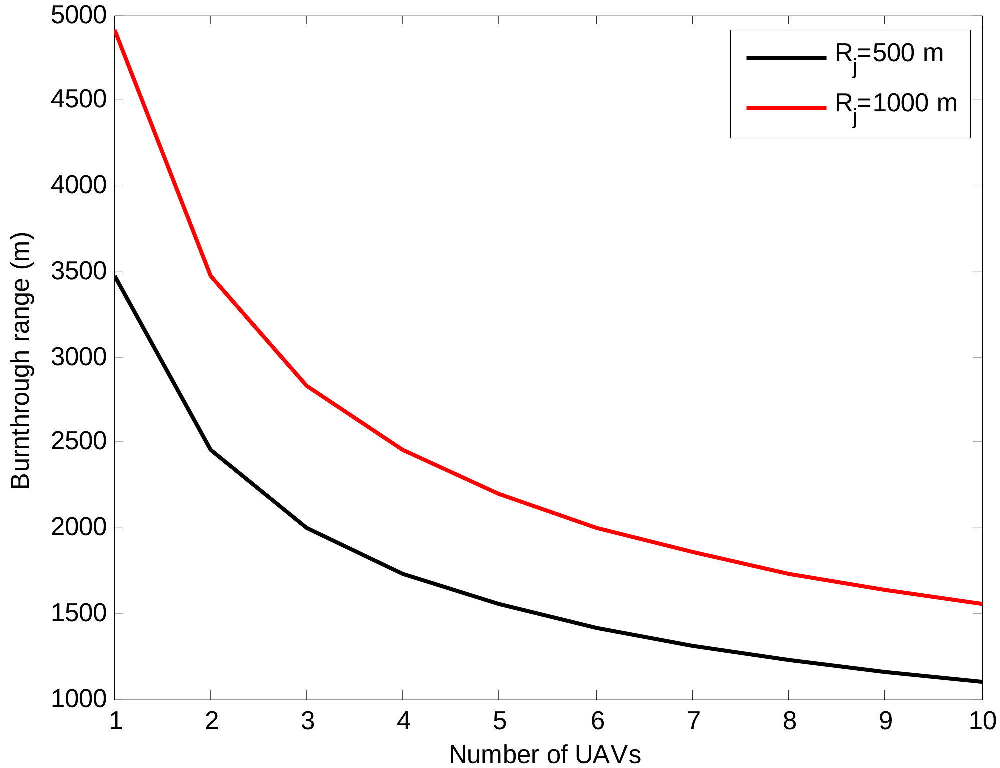

Figure 21. Burnthrough range of screened aircraft vs. number of coherent jammer UAVs.

For comparison to the initial single UAV scenario, the detection characteristics for swarms of 5 and 10 UAVs are shown in Figures 22 and 23. The spread of the swarm is considered small, so that $R_n \approx R_j$ in Figure 19. This may not be a valid approximation at very close ranges.

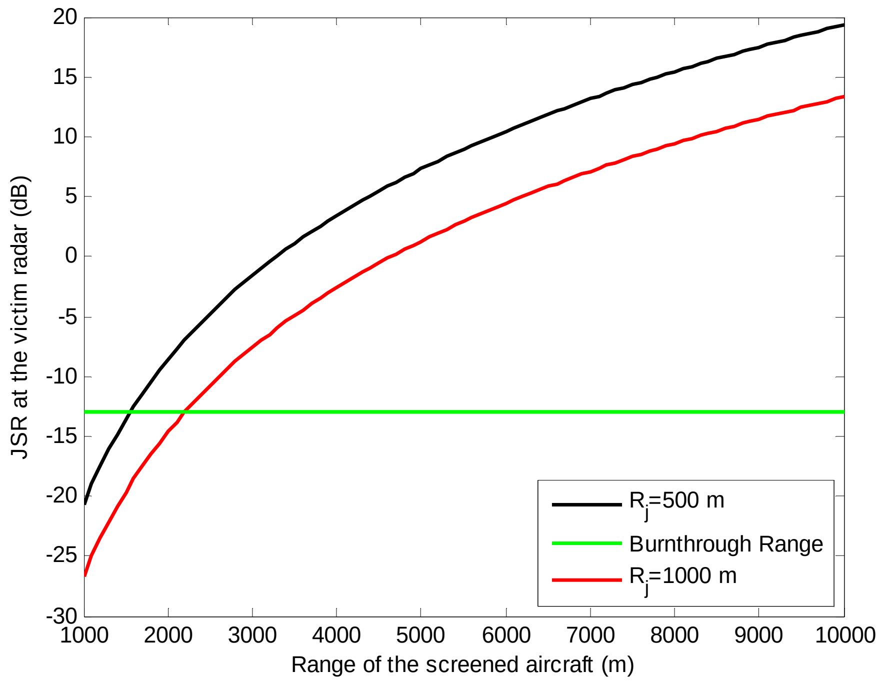

Figure 22. Detection characteristics of SA-2 Fan Song radar vs. 5 coherent jammer UAVs.

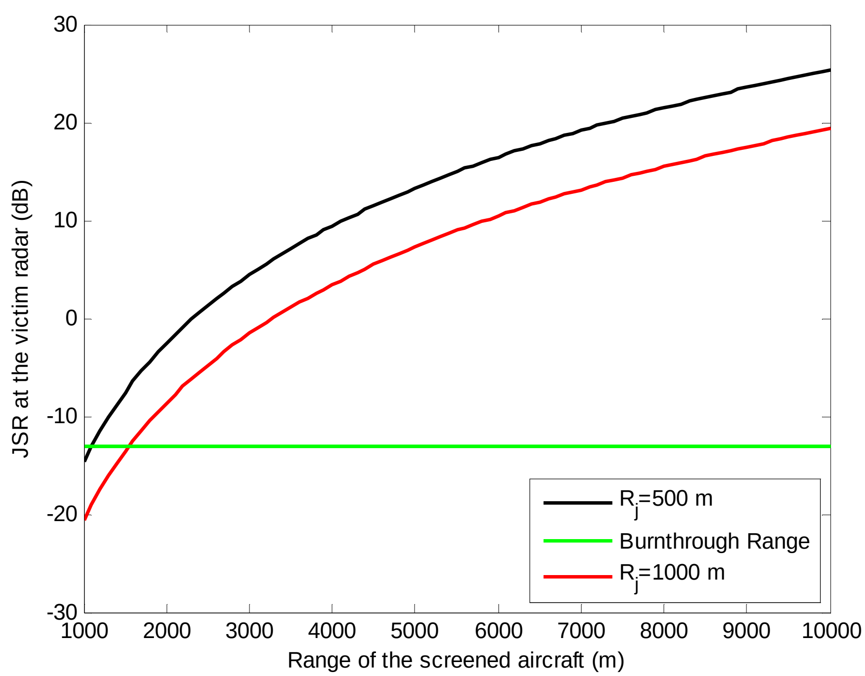

Figure 23. Detection characteristics of SA-2 Fan Song radar vs. 10 coherent jammer UAVs.

It is clearly seen from Figures 22 and 23 that more swarm elements provide significantly reduced burnthrough ranges to the screened aircraft. In both figures, smaller detection regions (below the -13 dB threshold line) along with larger effective jamming regions (above the line) occur when compared to those of the single jammer UAV results shown in Figure 20. Thus, by this application, using UAVs emitting relatively low power signals, the Jamming-to-Signal Ratio for the EA mission is enhanced when operating in the wireless networked and swarmed mode.

When non-coherent integration of the UAVs is considered, the burnthrough ranges become larger while the JSR achieved at the victim radar becomes smaller than the coherent case just considered. For non-coherent jamming the total jamming power increases as N according to Equation (2.34) as opposed to the increase of N^2 in coherent jamming. Figure 24 shows the resulting burnthrough ranges versus the number of jammer UAVs for both $R_j = 500$ m and $R_j = 1000$ m jammer ranges for non-coherent jamming.

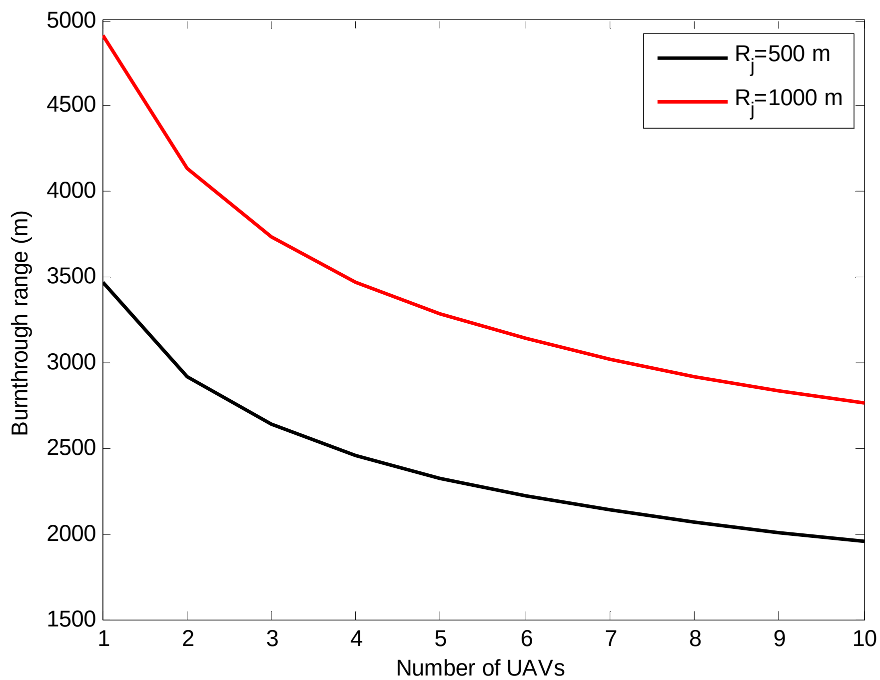

Figure 24. Burnthrough range of screened aircraft vs. number of non-coherent jammer UAVs.

Figure 24 shows that not only the burnthrough ranges for the screened aircraft, but also the difference between the burnthrough ranges for $R_j = 500$ m and $R_j = 1000$ m jammer ranges becomes larger. As smaller burnthrough ranges are desired, non-coherent operation apparently causes degradation in jamming performance.

For comparison to the coherent jamming scenario, the detection characteristics of the SA-2 Fan Song radar for swarms of 5 and 10 non-coherently operating jammer UAVs are shown in Figures 25 and 26, respectively.

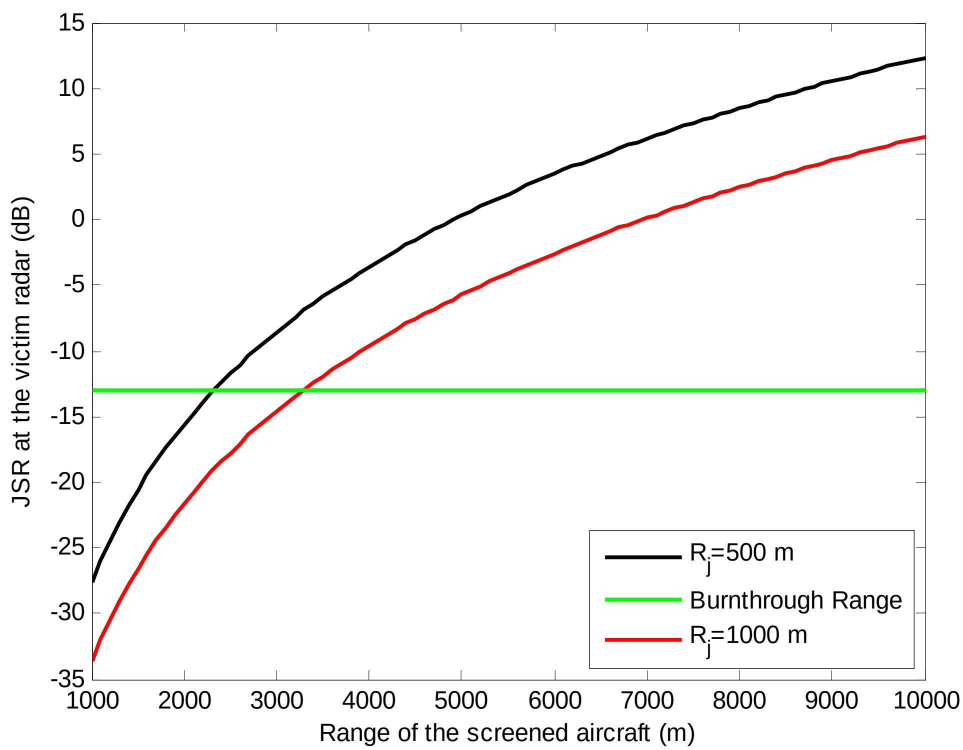

Figure 25. Detection characteristics of SA-2 Fan Song radar vs. 5 non-coherent jammer UAVs.

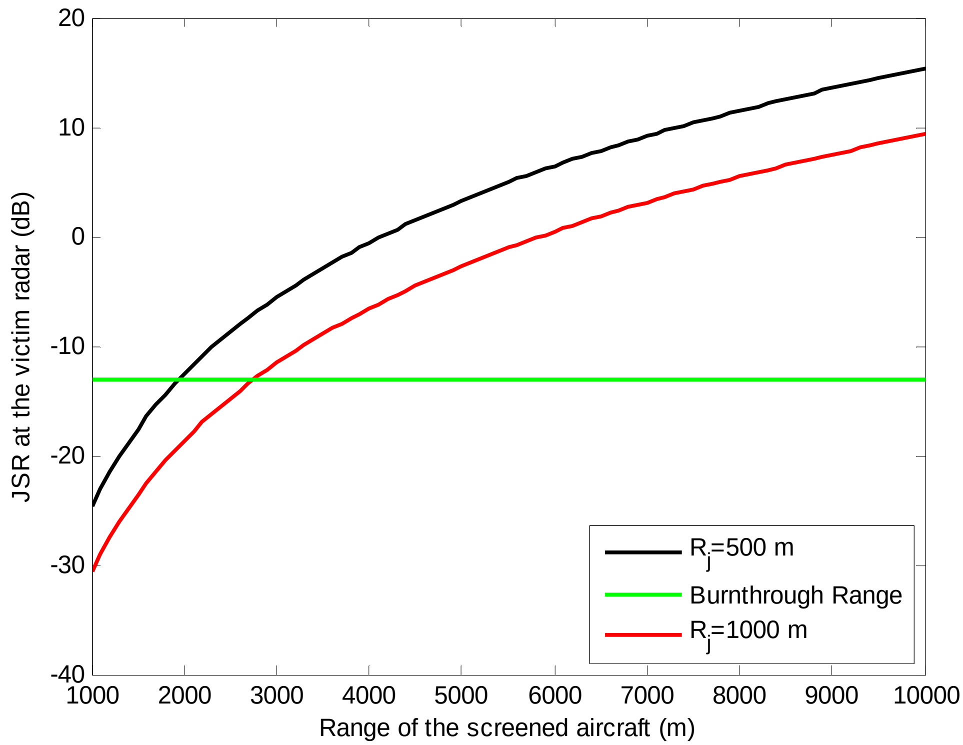

Figure 26. Detection characteristics of SA-2 Fan Song radar vs. 10 non-coherent jammer UAVs.

When Figure 25 is compared to Figure 22 and Figure 26 is compared to Figure 23, it is seen that the achieved JSR values at the Fan Song radar is about 10 dB lower for the non-coherent cases. The non-coherent burnthrough range is still lowered as the size of the UAV array increases (N=1 to 5 to 10), but the N^2 property of a coherent array provides the largest influence. The main result of this comparison is that coherent operation is an important parameter for enhancement of the jamming performance.

2. Detection of Adversary Order of Battle

Detection of adversary order of battle is crucial to the success of any military campaign. Military commanders need all kinds of order of battle information about the adversary such as air order of battle (AOB), ground order of battle (GOB), naval order of battle (NOB), and electronic order of battle (EOB). These are mostly provided by ground based detection radars or airborne command control (C2) assets. In our case, given that an enhanced range is potentially provided by beamforming of elements carried by a swarm of UAVs, the digitally formed beam may be utilized for detection purposes. A great advantage is that the detection assets (UAVs) will be low observable platforms when compared to a single manned platform or a ground based array antenna which can provide the same range.

With signals intelligence payloads, micro-air vehicles could assist in enemy electronic order of battle determination to include emitter types and locations. It would take several MAVs so equipped to perform emitter location through the time-difference-of-arrival technique but this would require extensive avionics miniaturization and access to a good time standard, perhaps through GPS. Another possibility is a MAV payload optimized for communications intercept to assist in intelligence activities by capturing emission externals (frequency, waveform, etc.) or internals (voice, data, etc.) [16].

3. Detection of Forward Deployed Ballistic Missiles

Detection of forward deployment of ballistic missiles is another possible application of UAV-borne opportunistic arrays. Tong [10] suggests an application of opportunistic arrays for ballistic missile defense (BMD). Swarm UAV-borne opportunistic arrays may be utilized for the same purpose. If a worthwhile enhancement in range is realized in a swarm UAV-borne opportunistic array, the swarm flying over friendly territories (in low threat environments) may provide early detection and tracking of ballistic missiles. In case a worthwhile range enhancement is not possible, the swarm UAV-borne opportunistic array is still an alternate solution since it consists of low observable platforms and thus can fly over adversary territories at lower risk.

D. OPERATIONAL ADVANTAGES OF UAV-BORNE OPPORTUNISTIC ARRAYS

1. Low Power Requirements

Consider a single large jammer platform with either Self Screening Jamming (SSJ) or Stand-in/Stand-off jamming mission. Then, alternatively, consider either a single

UAV or a swarm UAV network with distributed beamforming realized for a jamming mission. Given these two scenarios, calculate the necessary transmitter power required for providing the same burn-through range for both cases. Comparing the power required would generally show the low power advantage for the UAV case.

2. Low Observability

Low power requirements will provide a capability of low observability to the individual elements of the UAV network. In case of emergent adversary recognition, due to its highly mobile and reconfigurable structure, the swarm UAV network can be distributed over a large area for self-protection purposes. After negating the adversary attack, the beamforming network can be restored for resuming full operation in a relatively short time.

3. Reduced Risk

Low power requirements and the related low observability capability will yield a reduced risk while sustaining the advantages of a stand-in jammer.

The risk of losing the component in entirety is also reduced. Even after a considerable fraction of the total number of UAV swarm elements are downed by adversary actions, the remainders still provide a square-law contribution and comprise a swarm capable of jamming.

4. Mission Sustainability and Reduced Cost

As the risk of losing the whole component is reduced, the jamming mission sustainability is increased. Even if a very low percentage of swarm elements contribute to beamforming, there is still beamforming gain.

UAVs are relatively cheap platforms when compared to larger manned aerial vehicles. A moderate mini-UAV, necessarily equipped to participate in a beamforming swarm, can cost around $2,000. A swarm of even hundreds of such UAVs will be cheaper when compared to a manned aircraft. However, if coherent beamforming is employed, more advanced hardware is required, which will drive up the cost and weight.

E. OTHER POSSIBLE APPLICATIONS

Besides the aforementioned primary applications, UAV-borne opportunistic arrays might have several other civilian and military applications.

1. Civilian Applications

The increased availability and low cost of opportunistic array applications on UAV swarms may make them commercially attractive. Recalling the multi-satellite high resolution imaging system considered by by Lee and Dorny [14], the concept of beamforming in opportunistic arrays of UAVs may be applied on multi-satellite systems for commercial communication purposes.

Another civilian application may be disaster relief. An application of opportunistic arrays for such purposes is proposed by Tong [10] recalling the Southeast Asian tsunami on 26 December 2004. After such events, lack of communication links and air traffic control facilities may increase the risk faced by humanitarian aid personnel and aircraft. Furthermore, the disaster area may pose health risks to the crew of any kind of manned craft. In such cases UAVs may be an alternative and UAV-borne opportunistic arrays may be employed for communication and reconnaissance purposes.

2. Other Military Applications

The abovementioned commercial applications may well be used for military purposes. Military satellite imaging and communication systems may be built utilizing the beamforming concept of UAV-borne opportunistic arrays.

Another possibility may be employing such arrays in combat search and rescue (CSAR) missions for reconnaissance purposes or employing UAVs over areas where health risks for the crew of manned platforms is a possibility in cases like chemical, biological or nuclear warfare.

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IV. FEASIBILITY OF WIRELESS BEAMFORMING IN A UAV NETWORK

Up to this point the potential advantages of utilizing a swarm UAV wireless beamforming network have been presented stating that element location and synchronization are givens. In this chapter, these challenges and possible solutions to them will be discussed.

A. REQUIREMENTS AND DIFFICULTIES

In a mobile network of UAVs the relative locations of elements will continuously change. However, in a wireless beamforming network the beamformer (the master UAV for our case) needs to know the locations of each contributing element to an acceptable level of accuracy. Another important requirement is that the beamforming elements should be synchronized in time and phase.

1. Geolocalization Problem

Element localization or knowledge of the elements' position is crucial to the performance of digital beamforming. Due to the mobile structure of the UAV swarm, a major challenge is the geolocation of the elements of the swarm. If available, every single UAV element can be programmed to send a position information signal to the master UAV (or the base station if applicable) at a certain time. Wireless communication parameters within a swarm UAV network must be robust enough to assure that the master element has information about the location of all other contributing elements to a sufficient level of accuracy.

A general rule of thumb for tolerable errors in the position knowledge of elements is a fraction of the wavelength ($\lambda/10$) [4]. Following this approach, for the 2.45 GHz carrier frequency and the corresponding operating wavelength of approximately 0.1224 m of a wireless UAV beamforming network, the tolerable position error would be 0.0122 m which is equal to 1.22 cm. Such a stringent positioning error is about the best achievable by GPS under the most favorable conditions [5].

2. Synchronization Problem

In order to achieve full advantages of a UAV swarm wireless beamforming network, time and phase synchronization of the elements are also major challenges to be addressed. Time and phase synchronization of elements ensures that transmitted signals from all array elements converge coherently at the target, which consequently increases the average power and signal-to-noise ratio.

Imperfect synchronization in time can be due to imperfect geolocalization of the elements or imperfect synchronization of the separate UAV local oscillators to a common reference.

It is useful to list these two levels of synchronization and their associated sub-requirements for the general case of two-way full coherence problem in distributed arrays [27]:

(a) Time synchronization: On transmit (downlink), transmitted pulses from all array elements should be timed so that they can maintain an adequate degree of overlap at the base station. Similarly, on receive (uplink) signals from the base station to each individual element should be necessarily delayed at the receive processor so as to achieve a similar degree of overlap at the array output. In order to achieve time synchronization, the following two requirements should be met [27]:

(1) A method for real time estimation and application of the necessary time delay adjustments should be devised.

(2) A high resolution time reference (clock signal) should be distributed throughout the array so that useful time measurements can be made.

(b) Phase synchronization: The phases of the transmitted signals from the individual array elements (downlink) should be adjusted so that they all add in phase when they arrive at the base station. Similarly for uplink, the receiver phase values should be adjusted so that the BS signal adds in phase at the array processor output. In order to achieve phase synchronization, the following two requirements should be met [27]:

(1) A method for real time estimation and application of the necessary phase adjustments should be devised.

(2) A phase reference should be distributed throughout the array so that useful phase measurements can be made.

3. Transmission Losses and Range Limitations

Transmission losses and range limitations are problems for communications in any domain. These problems are even greater in wireless communications. For a single platform based wireless beamforming application such as a shipboard opportunistic array, the distance of the array elements to the beamformer cannot exceed the ship dimensions. Thus the transmission losses can be compensated. Furthermore, the available power for the array elements and the beamformer circuitry are relatively high when compared to the available power levels at any small sized UAV.

Power management of UAVs in general is a highly researched area. Efforts focus on increasing the percentage of useful power which may be defined as the power dedicated to the specific mission and applications excluding the power used for normal flight requirements of the platform. So the dedicated power to the T/R modules onboard the UAVs in a swarm are limited. For realization of distributed beamforming in a swarm network, wireless communication between the elements and the beamformer (or the master UAV) must be maintained. When the swarm elements are distributed over large areas, the ranges from the individual elements to the beamformer should be traded-off with the available power levels.

B. POSSIBLE SOLUTIONS TO THESE DIFFICULTIES

1. Possible Solutions to the Geolocalization Problem

Loke [4] suggests that imperfect geolocalization of elements would cause effects such as reduction in gain, beam pointing errors and increase in sidelobe levels. He then presents a survey of position location techniques including:

(a) Global Positioning System (GPS) based systems

(b) Wireless local area network (WLAN) based systems

(c) Ultrasound based systems

(d) Frequency modulated continuous wave (FMCW) radar systems

(e) Ultra-wideband (UWB) based systems

The above listed techniques mainly depend on achieving position location of elements by measuring distances from multiple reference points. They use one or more of the following distance measurement methods in a wireless environment:

(a) Time of flight (TOF) measurement: Transmitting a signal with a certain velocity from the reference point to the object and measuring the time of flight (TOF) to obtain the distance. This requires perfect synchronization of all receivers and transmitters

(b) Time difference of arrival (TDOA) measurement: For imperfect synchronization of transmitters and receivers, transmitting two or more signals simultaneously and measuring the time difference of arrival to obtain the distance.

(c) Angle of arrival (AOA) measurement: Using angles to calculate distance. This method requires accurate angle information, typically using phased arrays with multiple antennas and known separation to perform angular calculation.

(d) Received signal strength (RSS) measurement: Utilizing the attenuation knowledge of the medium and using a function of attenuation to obtain the distance of a transmitted reference signal by measuring the received signal strength at the receiver [4].

Considering these suggested techniques utilizing the above methods of distance measurement, the best technique addressing the geolocalization problem depends on the application. Experimental results may be utilized for determining the best technique. All of these techniques are degraded due to the motion of the UAVs, and very fast update rates are required.

2. Possible Solutions to the Synchronization Problem

Within the general concept of distributed arrays, two techniques are generally offered to achieve synchronization [2, 4]:

a. "Brute Force" Synchronization Technique

The brute force synchronization technique depends on systematic adjustment of the array element phases [4]. It can be implemented by incorporating a synchronization block within the hardware design architecture of each array element. In the “brute force” phase synchronization technique a continuous wave (CW) signal is send to an element, which introduces a phase shift, and then returns it back to the controller. This process is repeated for several phase values and the necessary phase shift is determined when the peak output of a detector is observed. This iterative process, which is repeated for all array elements, is generally an inefficient approach, but maybe adequate if large phase errors are tolerable. Then phase convergence can be achieved in just a couple of iterations [2, 4]. The general concept of performing phase synchronization for a single array element is shown in Figure 27.

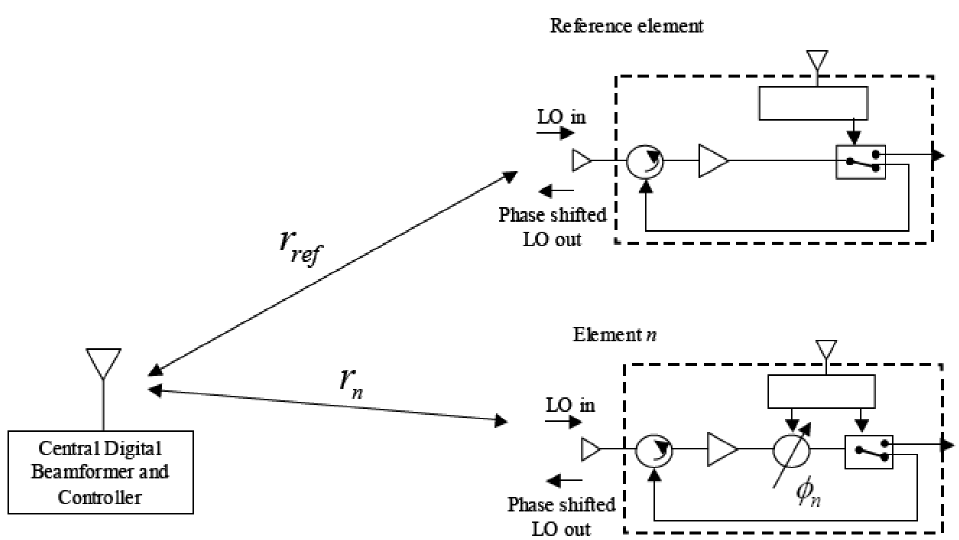

Figure 27. Phase synchronization using the brute force technique (From [4]).

The circuit in the dashed boxes can be modified to include a local oscillator and a phase locked-loop (PLL). The beacon from the central controller would serve as a reference to which the PLL could be synchronized. Note that the elements are synchronized one at a time, and therefore this technique is very time consuming.

b. "Beam Tagging" Synchronization Technique

In beam tagging technique, low-index phase modulation is applied to one of two signals aimed at the same receiver, and resulting amplitude modulation is measured to provide the phase alignment between the antennas [4]. Phase synchronization of an element using beam tagging technique is shown in Figure 28. With more sophisticated phase modulation circuits, unique orthogonal codes could be assigned to each element. It would then be possible to synchronize all elements simultaneously, reducing the required time.

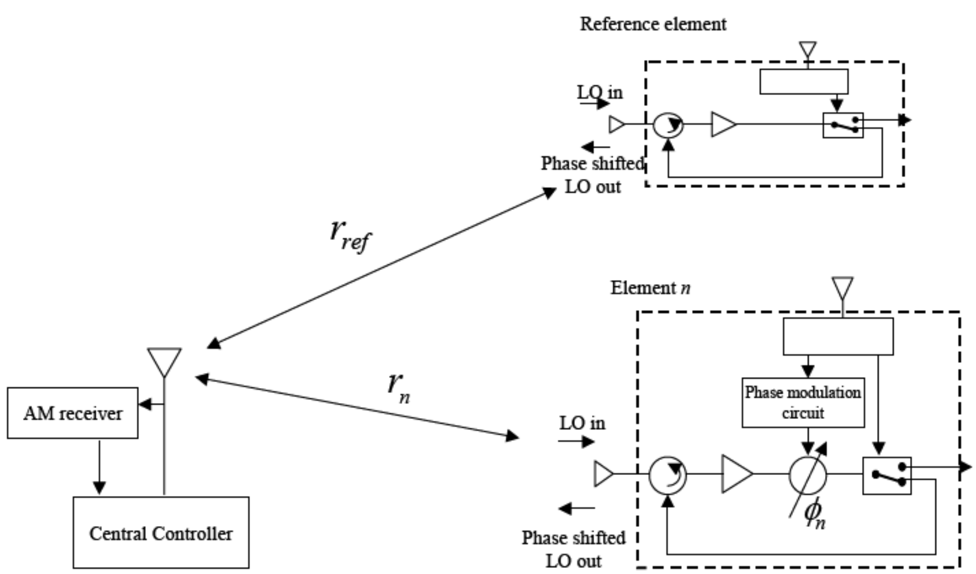

Figure 28. Phase synchronization using the beam tagging technique (From [4]).

When compared to brute force, the hardware is more complicated in beam tagging. A phase modulation circuit is added on the element synchronization block and an amplitude modulation (AM) receiver circuitry is added on the beamformer [4].

Among the two techniques, brute force synchronization is a simple technique which can be implemented with a synchronization circuitry at each element and the beamformer. On the other hand, while the beam tagging synchronization technique requires less time, it requires hardware complexity [4].

The abovementioned techniques are mostly considered for the general case of single platform wireless beamforming applications. Thus they might not yield the desired results in a multi-platform based case such as a UAV swarm beamforming network. For the UAV swarm beamforming network, the following two synchronization approaches may be more suitable:

(1) Mutual synchronization technique

(2) Master-slave synchronization technique

Many references [3, 5, 6, 7] give details about these synchronization techniques. So, a brief summary of each technique is presented in this work.

c. Mutual Synchronization Technique

This technique is preferred when no clock is superior to others and the robustness of the common time scale, with respect to the drift of any clock, is very critical. With mutual synchronization, each clock collaborates with other clocks to determine the common time scale. Once the relative differences in time and phase are determined for all elements, compensation can be provided in beamforming and waveform generation. There are two drawbacks associated with this synchronization method. The first drawback is the significant overhead, which consumes time and energy, is required for clocks to determine the common clock scale. Secondly, a multiple access or coding scheme must be employed to differentiate one clock from the other [5, 6].

d. Master-Slave Synchronization Technique

The clock drift is not an issue for the master-slave synchronization technique, because each slave clock is capable of keeping track of the variations of the master clock. Pre-compensation is required for each transmit antenna to compensate unequal propagation delays. In a network synchronization concept, the propagation delays from the master clock to the slave clocks are compensated either in the master clock in advance or in the slave clocks afterwards, so that at any time, all clocks have the same time scale.

It is desired that the waves are arrive at the receive antenna coherently, which is similar to time requirements for the time division multiple access (TDMA) in satellite communications, where signals from transmit antennas must arrive at the satellite at specified times. If the delays from all transmit antennas to the receive antenna are the same, the result is just a shift of the time scale, and all signals can arrive coherently. However, because the delays are actually different, clocks in transmit antennas have to be pre-compensated to account for different propagation delays from the transmit antennas to the receive antenna. Thus, the delays from the master to the slave clocks have to be compensated, and the delays from the transmit antennas to the receive antenna must be pre-compensated [6].

Two types of combination of master-slave synchronization and pre-compensation are considered in [5, 6]:

(1) Open-loop master-slave synchronization is the first type. For a master-slave pair, both master and slave antennas transmit their clock scales to each other. Based on the clock scales of the incoming waves and the local antenna, the clock difference and pre-compensation are constantly calculated cooperatively by the master and the slave antenna. The slave clock accordingly updates its clock and pre-compensation by changing delay, while the master updated the pre-compensation only. The slave clock makes no effort to adjust its oscillator frequency in response to the clock difference. If the master and the slave oscillator frequencies are off by a large difference, the clock difference will increase rapidly after updates. The result will be poor synchronization or the need to re-synchronize frequently.

(2) Closed-loop master-slave synchronization is the other choice. In this approach, the slave clock is a voltage controlled oscillator (VCO). The error signal is the clock difference mentioned above, and this signal is used to adjust the

VCO frequency as opposed to the delay as in the open-loop approach. The problems with closed-loop approach are the stability and the tracking ability. Unlike ordinary phase lock loops, this loop includes two significant delays, one in the master-to-slave transmission and the other in the slave-to-master transmission. Since the delay is so huge, to keep the loop stable, the loop bandwidth is kept narrow, and the tracking ability is reduced [6].

Since the main goal is to align all EM waves so that they coherently converge at the receiver antenna with little extra energy dissipation, whether the common energy scale is robust or not, the master-slave synchronization approach may be a better choice [6].

Reference [7] considers a master-slave architecture for beamforming and presents a protocol for achieving phase synchronization based on the master slave architecture shown in Figure 29.

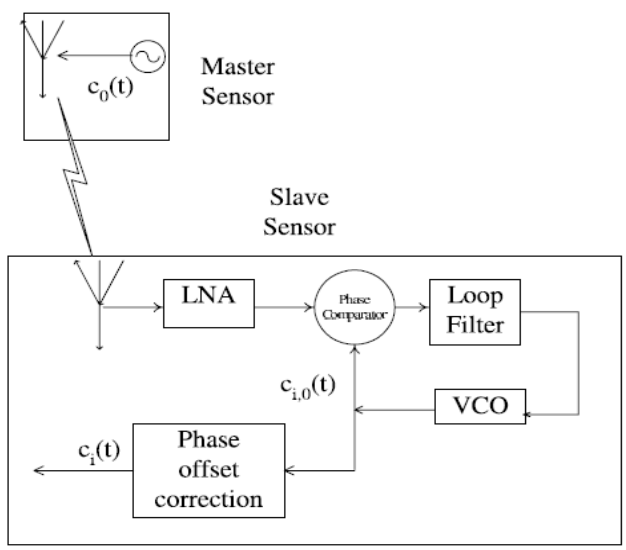

Figure 29. Master-slave architecture for carrier synchronization (From [7]).

The idea behind the proposed master-slave protocol, as referenced from [7] is as follows:

The master sensor local oscillator generates a sinusoid $c_o(t)$:

$$c_0(t) = \Re\left(\tilde{c}_0(t)\right), \text{ where } \tilde{c}_0(t) = e^{j(2\pi f_c t + \gamma_0)} \tag{4.1}$$

This sinusoid serves as the reference signal for the network and the master broadcasts it to all the slaves. The local communication channel between master and slave sensors is assumed to have a large SNR and the receiver noise in this channel is ignored. After reception and amplification, the slave sensor *i* receives the signal broadcast by the master as:

$$c_{i,0}(t) = \Re\left(\tilde{c}_{i,0}(t)\right), \text{ where } \tilde{c}_{i,0}(t) = A_{i,0}e^{j(2\pi f_c t + \gamma_0 - \gamma_i)} \tag{4.2}$$

where γ_i is the phase shift between the master and slave and $A_{i,0}$ is the amplitude of the received signal. For convenience the term $A_{i,0}$ can be set to unity and the constant γ_0 to zero.

The sensor *i* uses the signal $c_{i,0}(t)$ as input to a second-order phase locked-loop (PLL), driven by a VCO with a quiescent frequency close to f_c. The steady-state phase error between VCO output and $c_{i,0}(t)$ is zero, so the steady-state VCO output can be used as a carrier signal consistent across all sensors, given that the offset γ_i can be corrected for. This concept is shown within the PLL theory which is presented in [29], and therefore will not be detailed here.

The phase offset γ_i is the total phase shift between the master sensors' reference oscillator signal $c_0(t)$, and the input signal at the slave sensors' PLL to which the slave VCO is synchronized in steady-state. Another contribution to γ_i is from the phase response of the RF amplifiers at the master and slave sensor. These offsets are fixed and precisely known, and therefore, can also be corrected for [7].

For the purposes of this study only the key concepts of synchronization in distributed beamforming is presented in a general sense. However, it should be noted that the dynamic network geometry considered for a swarm UAV beamforming network causes greater synchronization problems.

Most of these phase and time synchronization techniques are adequate when the elements are close together and stationary. When the elements are moving and far apart, synchronization is extremely difficult due to Doppler shifts and system latency (delays due to propagation, electronics and processing).

e. Imperfect Synchronization

The desired synchronization may not be achieved in a UAV swarm beamforming application. So it is meaningful to consider the beamforming performance for poor synchronization cases.

It is noted in [7] that even with imperfect phase synchronization, the achievable beamforming gains in wireless networks are substantial, i.e. the factor of N in Equation (2.33). This is concluded in [7] by considering a simple example with the following steps:

(1) Two equal amplitude signals from two transmitters with relative phase error of δ combine at a base station.

(2) The resulting signal amplitude is given by

$$\left|1+e^{j\delta}\right| = 2\cos\left(\frac{\delta}{2}\right) \tag{4.3}$$

(3) The maximum signal amplitude is achieved when $\delta = 0^0$ and the maximum possible amplitude is 2.

(4) When a significant phase error of $\delta = 30^0$ is considered Equation (4.3) gives approximately 1.932 which is 96% of the maximum achievable amplitude. Table 4 shows the achieved signal amplitudes and relative losses referenced to the ideal case of zero phase error.

Phase error (degree)	Achieved signal amplitude	Loss when compared to the ideal case (dB)
0	2.000	0.00
30	1.932	0.15
45	1.848	0.34
60	1.732	0.62
90	1.414	1.51
120	1.000	3.01
150	0.518	5.87
180	0.000	N/A

Table 4. Signal strength at BS from two transmitters with relative phase errors from 0^0 to 180^0.

The zero phase error case in Table 4 corresponds to the ideal case of two perfectly synchronized transmitters. Phase errors from 30^0 to 180^0 represent the imperfect synchronization cases. A 180^0 phase error is considered to be the worst case scenario where completely destructive interference between the transmitters occurs. In other cases the interference is still constructive and beamforming gains are still significant. Even with considerably large phase errors such as 60^0 or 90^0, more than 70% of the gains are sustained.

In this chapter a brief feasibility analysis of distributed beamforming in UAV swarms was presented. The key concepts of synchronization and element geolocalization were taken into consideration while possible hardware and software solutions to the outstanding difficulties are discussed.

It was also indicated in this chapter that adequate synchronization may not be achieved for swarm UAV beamforming networks. Thus, the effects of imperfect synchronization on the beamforming performance were also discussed.

V. CONCLUSIONS AND RECOMMENDATIONS

A. SUMMARY

The research objective of this study was to examine and evaluate distributed beamforming performance in a UAV swarm network. The main approach was to present a feasibility analysis of merging several concepts such as "UAV swarming," "opportunistic arrays," and "distributed beamforming" and in terms of the application "RF jamming."

UAV swarming and its associated subjects, such as swarm behavior and swarm control, were introduced together with present military applications of UAVs and UAV swarms. Specific advantages of UAV employment within different warfare types were discussed.

The wireless beamforming concept was presented within a basic UAV and victim radar (base station) geometry, and the downlink and uplink transmission equations were derived. Basic requirements and difficulties so as to realize distributed beamforming in wireless networks was surveyed. After that, possible challenges specifically associated with UAV-borne opportunistic arrays were considered. Major challenges, such as element geolocalization and time and phase synchronization, were addressed, and possible solutions were considered. Wireless beamforming performance with imperfect synchronization was also discussed.

Analysis of jamming performance for a considered SOJ scenario with SA-2 Fan Song radar was presented in detail. The relation between the number of jammer UAVs and the achieved JSR at the victim radar were analyzed. Throughout the analysis successful synchronization of swarm elements was assumed. The concept of collective beamforming in random arrays was utilized where appropriate synchronization was not possible.

B. CONCLUSIONS

The main conclusion of this thesis is related to its primary research objective, which as aforementioned was evaluation of merging of the concepts of distributed wireless beamforming and UAV swarming. Noting that certain outstanding difficulties still exist, the overall conclusion is that merging these two concepts is viable and yields operational advantages in terms its military applications.

1. Advantages of Merging the Two Concepts

Recalling the EA jamming application analyzed in Chapter III, the operational advantages of a swarm UAV wireless beamforming network include:

(a) Low power requirements

(b) Substantial gain in range capabilities

(c) Low observability

(d) Reduced Risk

(e) Mission sustainability

(f) Reduced cost

Among these advantages, low power requirements and substantial range enhancement were analyzed in detail. It was shown that with very low single UAV transmitter power levels (such as 100 mW which is used in jamming performance analysis) effective radar jamming could be realized and significant operational range enhancements for friendly forces were achieved.

2. Outstanding Difficulties

The outstanding challenges so as to realize swarm beamforming networks are no different from the challenges of the conventional beamforming opportunistic array concepts. But the difference is that these challenges are even greater in the UAV case and are less addressable. The key challenges of beamforming in a swarm UAV network include:

(a) The problem of geolocation of elements to an acceptable level of accuracy

(b) Synchronization of UAV T/R modules in time, frequency and phase

(c) Transmission losses, latency, and range degradation introduced by the wireless nature of communications within the swarm.

The swarm and the parameters of specific applications may be traded off in such a way that they can meet the limits in term of transmission losses and range degradation. However, the geolocalization and synchronization challenges may not be adequately addressed in a UAV swarm network for most of the applications.

C. RECOMMENDATIONS FOR FUTURE WORK

Future work can focus on the outstanding challenges mentioned above. Possible ways to provide geolocation of elements in a timely manner and with adequate accuracy may be studied. More work can be done about imperfect synchronization while effects of large synchronization errors (phase errors in RMS sense) on the beamforming performance may be examined by simulations. While a brief discussion about the effects of imperfect synchronization on the beamforming performance was presented, the effects of imperfect geolocation were not discussed to the same extend and is left for future work.

From the applications perspective, the EA jammer application proposed in this thesis may be studied in terms of the jamming waveform. Since, synchronization is still an outstanding issue, mostly a noise jammer was considered in this study. Future work may focus on specific waveforms to be employed at the jammer assets. This may extend the capabilities of the jammer UAV swarm over the desired bands and with incorporating a wavelength selection algorithm or a pre-programmable controller, jamming may be executed better in more dynamic operational environments.

The UAV swarming concept may also be researched considering several different swarm configurations and analyzing the beamforming performance these configurations in order to determine the parameters that can be traded off. Similarly, the design of single swarm element may also be focused on by means of both hardware and software studies.

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   Naval Postgraduate School
   Monterey, California

5. Terry Smith
   Lt. Col. USAF
   Department of Information Sciences
   Naval Postgraduate School
   Monterey, California

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